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PERMANENT MAGNET AND SUPERCONDUCTING GENERATORS IN AIRBORNE, HIGH-POWER SYSTEM

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Power Systems Branch
Aerospace Power Division

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This report presents results of a study performed to compare airborne, high power supplies at power levels of 10 and 20 MW utilizing permanent magnet and superconducting generators. Algorithms for the weight and volume of these electrical generators are presented and algorithms for the other power supply components are used to predict total system weights for seven point designs at the two power levels.

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FOREWORD

This Technical Report was prepared by the Power Systems Branch of the Aerospace Power Division (AFAPL/POP-2), U. S. Air Force Aero Propulsion Laboratory. The work described was performed under Project 3145, Task 32, Work Unit 21 (Studies Concerning Advanced Power Systems) by Capts Hugh L. Southall and Frederick C. Brockhurst, Project Engineers. This work took place over the period from 1 Feb 1978 through 31 March 1979.

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INTRODUCTION

1.1 BACKGROUND

Prediction of weights, volumes, and efficiencies for components in power supplies for high-power (multi-megawatt) applications is an important first step in determining feasibility for use aboard aircraft with strict size and weight constraints. Such a power supply system is illustrated in Figure 1.

In 1975 and 1976, the U.S. Air Force Aero Propulsion Laboratory (AFAPL) sponsored several contractual programs under the name of the "High-Power Study" which resulted in computer programs predicting size, weight, and performance for every component of a power supply system like the one shown in Figure 1. Programs were developed for turbines (References 1, 2), electrical generators (including both conventional, iron-core, round rotor (Reference 2), and superconducting (References 2, 3) and power conditioning components (Reference 4). Some of these programs were detailed design programs, while others used curve fits to detailed point designs within the scope of the study and were therefore not useful for power or voltage requirements outside the valid parameter space of the study.

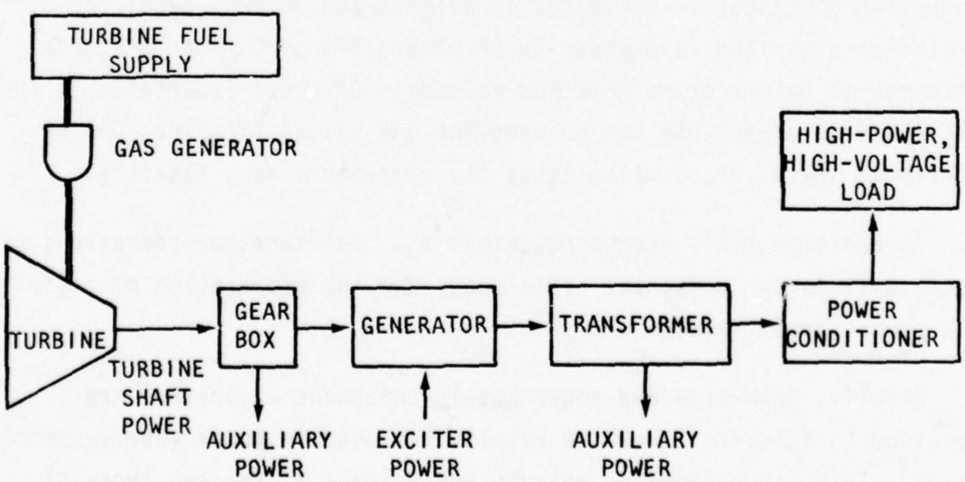

Figure 1. Generalized High-Power Airborne System

Since these studies were completed, the AFAPL has begun two development programs in advanced technology, second generation airborne electrical generators which are much different from the machines considered in the High-Power Study. One program is for the development of a prototype 5 MW permanent magnet generator (PMG) which would use high-energy-density samarium cobalt magnets for the field (Reference 5). The other program is a 20 MW superconducting generator using superconducting wire for the field coils and a conductive environmental shield (References 6, 7, 8). Algorithms developed in this report are specifically related to these two classes of electrical generators.

1.2 PURPOSE OF REPORT

This report presents simplified weight and volume algorithms for the two classes of advanced electrical generators discussed above and indicates how system weight is affected by the type of generator selected. The algorithms are simplified in the sense that they are not detailed design programs which consider every electrical, thermal, and mechanical aspect of electromechanical machine design. They are simplified, "approximate design," programs which use *fundamental* sizing relationships of electromechanical machine design coupled with current technology limits of the design parameters pertinent to advanced permanent magnet and superconducting generators. Estimates of weights and volumes predicted by the simplified algorithms are shown to be within 10% of current design estimates of generator weights and volumes. Of great importance is the fact that the algorithms can be used for any values of power, voltage, rotational speed, etc., which makes the algorithms very flexible.

In addition, this report describes the important considerations of system efficiency, component efficiency, and the propagation of efficiencies in a power supply system.

Finally, generator and power supply component algorithms are exercised to illustrate how the results are used in power supply system design. This study compares weights and volumes of the two types of generators at output power levels of approximately 10 and 20 megawatts. In addition, overall system weight is calculated for seven different point designs.

1.3 FUTURE WEIGHT AND VOLUME COMPUTER PROGRAMS

The ultimate goal is to have algorithms which give accurate weight and volume estimates for every component of the system shown in Figure 1 for a self-consistent total system size and weight. Indeed, as discussed in Section V, this is mandatory for a valid comparison of alternative power sources. Self-consistency means that all interface parameters between components must be taken into account. For example, the generator output voltage and frequency influence the size of the power conditioning subsystem. Although this can be done manually, as in Section V, an interactive, computer-aided power system design program has been developed under contract for this purpose (Reference 9). This program allows the interactive execution of all the computer programs developed under the High-Power Study to arrive at a total system weight and volume. Also, the program can be modified to accept new programs for advanced components, such as the permanent magnet generator, or to accept improved, revised, or new algorithms for other components.

SECTION II

POWER SUPPLY EFFICIENCY CONSIDERATIONS

Because of the influence on required prime mover and electrical power, it is important to analytically determine the effects of component efficiencies on the power supply system. Figure 2 illustrates a power supply system which supplies primary loads P_{L1} and P_{L2}, and auxiliary electrical power P_{AUX}. It should be noted that the generator exciter power (Figure 1) is assumed to be zero, which is valid for permanent magnet and very nearly correct for superconducting generators. The two primary loads are, in general, rated at different power and voltage levels. If the number two transformer were used to supply power to the number two primary load, the system would appear as in Figure 3. Component efficiencies are indicated above the block representing each component.

Efficiency is defined as

$$\eta = P_{out}/P_{in}, \tag{1}$$

where P_{out} is the power out of a component and P_{in} is the power into a component. Heat generated within each component is given by

$$P_{loss} = P_{in} - P_{out} = \frac{(1-\eta)}{\eta} P_{out}. \text{ (watts)} \tag{2}$$

From the definition of efficiency and the specification of the required output powers, P_{L1} and P_{L2}, the auxiliary electrical power requirement, P_{AUX}, and the auxiliary mechanical power requirement, $P_{MECH_{AUX}}$, the power requirement at any intermediate stage within the system can be determined if all the component efficiencies are known. For example, P_1, the input to the number one power conditioner can be found by dividing P_{L1} by η_1, i.e.,

$$P_1 = P_{L1}/\eta_1 \tag{3}$$

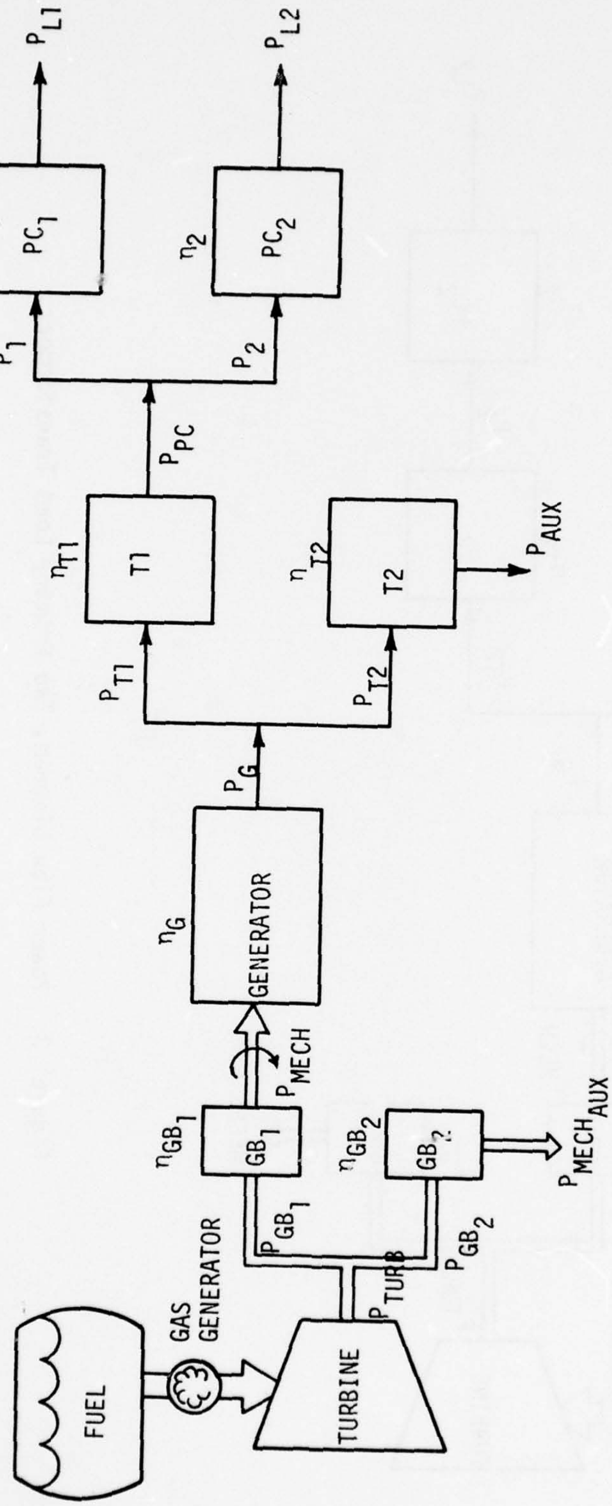

Figure 2. Power Flow Diagram, One Primary Load Transformer

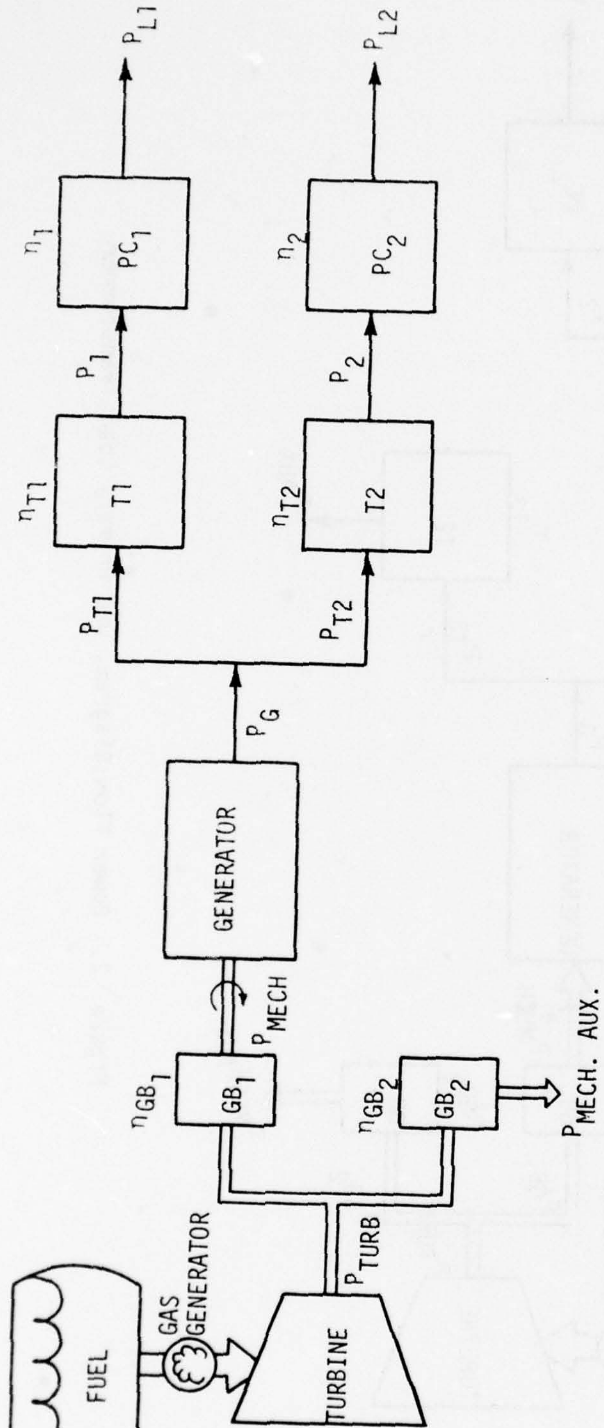

Figure 3. Power Flow Diagram, Two Primary Load Transformers

Powers at intermediate stages upstream can be calculated in a similar manner. Since the required output power of the generator, P_G, is of primary interest in this report, expressions for P_G are given for the systems shown in Figures 2 and 3. For the system with transformer T1 supplying both primary loads (Figure 2).

$$P_G = \frac{\eta_2 P_{L1} + \eta_1 P_{L2}}{\eta_{T1} \eta_1 \eta_2} + \frac{P_{AUX}}{\eta_{T2}}, \text{ (watts)} \tag{4}$$

and for the system where transformer T1 supplies one primary load and transformer T2 supplies the other primary load (Figure 3).

$$P_G = \frac{P_{L1}}{\eta_{T1} \eta_1} + \frac{P_{L2}}{\eta_{T2} \eta_2}. \text{ (watts)} \tag{5}$$

The mechanical shaft power which must be supplied by the turbine, for the system of Figure 2, is given by

$$P_{TURB} = \frac{\eta_2 P_{L1} + \eta_1 P_{L2}}{\eta_{GB_1} \eta_G \eta_{T1} \eta_1 \eta_2} + \frac{P_{AUX}}{\eta_{GB_1} \eta_G \eta_{T2}} + \frac{P_{MECH\ AUX}}{\eta_{GB_2}}, \text{ (watts)} \tag{6}$$

and for the system of Figure 3 by

$$P_{TURB} = \frac{P_{L1}}{\eta_{GB_1} \eta_G \eta_{T1} \eta_1} + \frac{P_{L2}}{\eta_{GB_1} \eta_G \eta_{T2} \eta_2} + \frac{P_{MECH\ AUX}}{\eta_{GB_2}}. \text{ (watts)} \tag{7}$$

Generator efficiency, η_G, is calculated as part of the generator algorithms. P_{TURB} is used in estimating the amount of prime mover fuel required, since fuel consumption is directly proportional to shaft power. Fuel weight is a major part of the overall system weight.

SECTION III

PERMANENT MAGNET HIGH-POWER GENERATORS

3.1 BACKGROUND

This analysis provides weight and volume estimates for iron-core alternators with permanent magnet field poles. The term "iron-core" is used to distinguish this class of machines, which relies upon a relatively small air gap and a high permeability iron path for the circulation of magnetic flux from rotor to stator, from machines which utilize relatively large air gaps (air-core machines). The field structure in the latter case must provide tremendous magnetomotive forces (mmf) to establish the required magnetic flux densities in the stator. Large air gap machines generally have superconducting field windings and are described in Section IV.

3.2 WEIGHT AND VOLUME EQUATIONS

The primary components of the alternator are indicated in Figure 4. They include the yoke (or back-iron), the teeth, the copper conductors and insulation in the stator, and the rotor. The total "electromagnetic weight" is the sum of the weights of these components. Total alternator weight is estimated by multiplying the electromagnetic weight by 1.20 to account for endbells, bearings, shafts, and structural material.

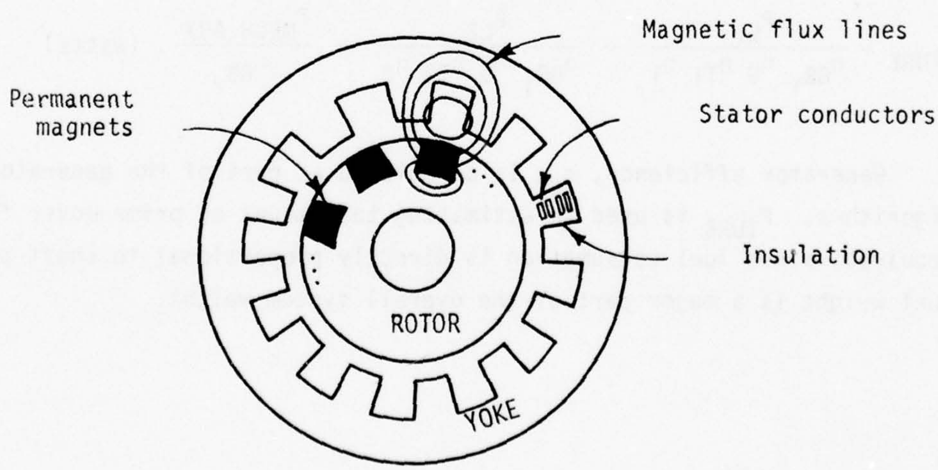

Figure 4. Conventional (Iron-Core) Alternator Radial Cross Section

Three fundamental relationships are used in sizing alternators. The rotor diameter is determined by the stress-limited tip speed, V_t, as follows,

$$D = \frac{720\ V_t}{\Pi\ RPM} \ . \quad \text{(inches)} \qquad (8)$$

Machine length can then be found from the generated phase voltage expression (Appendix A),

$$V_{ph} = 7.4018 \times 10^{-10} \times RPM \times K_W \times N \times D \times L \times B, \ \text{(volts rms)} \qquad (9)$$

where K_W is the winding factor, N is the number of series-connected turns per phase, $N = (p/PPATH)n_s C_s/2$, with p = number of poles, PPATH = number of parallel paths per phase, n_s = number of slots per pole per phase, C_s = number of conductors per slot, L is the stack length in inches, and B is the peak value of the fundamental sine wave component of flux density in the air gap in lines per square inch. The phase voltage calculated from Equation 9 is the open circuit phase voltage. Machine reactance will reduce the terminal phase voltage under load; however, since machine reactances are not calculated in the algorithms, this voltage regulation effect has not been included. The effect of machine reactance for sinusoidal, steady-state operation is to reduce the phase voltage at the terminals to a value given by

$$V_{ph\ (LOAD)} = \left\{ \frac{-b + \sqrt{b^2 - 4X_S^2\ P^2/(9PF^2)}}{2} \right\}^{1/2}, \ \text{(volts rms)} \qquad (10)$$

where $b = [(2X_s\ P\ \sqrt{1-PF^2}\ )/(3PF)] - V_{ph}^2$, X_s is the synchronous reactance in ohms, PF is the power factor of the load, P is the output power in watts, and V_{ph} is given in Equation 9. For any power output greater than zero, the terminal phase voltage under load, $V_{ph(LOAD)}$, will be less than the open circuit voltage V_{ph}. Thus, machines designed to use the algorithms presented in this report will supply the rated power; however, the rated voltage is somewhat high and the rated current is somewhat low, due to the fact that voltage regulation has been neglected.

For a given power output, power factor, number of phases, and phase voltage rating, the current per phase in the stator is given by

$$I_{ph} = P/PFn_{\phi}\ V_{ph}) \quad \text{(amps rms)} \qquad (11)$$

A generator design is obtained by iterating three different, independent design variables. These are: n_s (also equal to the number of single coils in a pole phase group as indicated in Figure 5); C_s (which is always an even number for a double layer winding); and PPATH.

The number of slots per pole per phase, n_s, is varied from 2 to 6 with n_s greater than or equal to 3 for permanent magnet machines to reduce pulsation losses. C_s is varied from 2 to 20 in increments of two. PPATH is varied from 1 to $n_s p$, where $n_s p$ is the number of coils per phase; however, only those values which divide evenly into $n_s p$ are considered. For example, if $n_s p = 8$, only the values 1, 2, 4, and 8 are used for PPATH. A double layer stator winding design is used for all iron-core alternators, as illustrated in Figure 5. $C_s/2$ conductors lie in an upper bar and $C_s/2$ in a lower bar within a slot.

□ = Phase A coil side
■ = Phase B coil side
▨ = Phase C coil side

Note: $n_s = 2$ (two slots, or coils, per pole per phase)

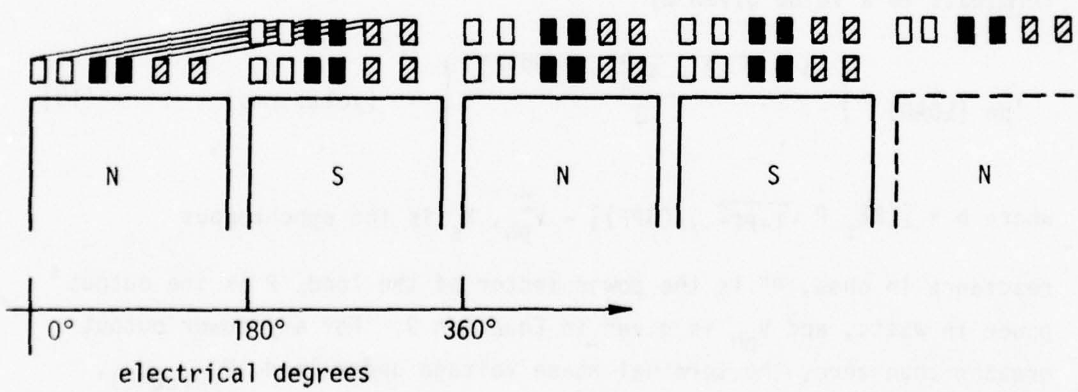

Figure 5. Stator Coil Arrangement for a Double Layer Winding With Full Pitch Coils

Required input parameters are listed in Table 1. Parameters listed in the first group are independent input variables which are specified to obtain a machine of the desired rating. The second group of input parameters are set by the present technology of high speed, high-power-density rotating machinery. For example, the stator bar current density is limited by the cooling capability of the stator. Given these inputs, the three independent design variables are varied to find a minimum weight machine. Several intermediate parameters of interest are:

(a) total number of active conductors in the stator

$$Z = n_s \, n_\phi \, p \, C_s = 2 \times PPATH \times n_\phi \times N \qquad (12)$$

(b) total number of slots

$$SLOTS = n_s \, n_\phi \, p \qquad (13)$$

(c) current per conductor

$$I_c = I_{ph}/PPATH \quad \text{(amps rms)} \qquad (14)$$

(d) specific electric loading (ampere conductors per inch of stator periphery)

$$Q_L = \frac{ZI_c}{\Pi D} = \frac{n_s \, C_s \, p}{PPATH} \times \frac{P}{PFxV_{ph}} \times \frac{RPM}{720 \, V_t} \qquad (15)$$

(e) slot width (Figure 3)

$$s = \Pi D \, (\alpha-1)/(\alpha n_s n_\phi p), \quad \text{(inches)} \qquad (16)$$

where α is the ratio of the magnetic flux density in the tooth to that in the air gap. From Figure 6(a), it can be seen that the tooth width is given by $s/(\alpha-1)$ when the assumption is made that the slot and tooth have straight sides.

TABLE 1

REQUIRED INPUT PARAMETERS FOR IRON-CORE ALTERNATOR DESIGNS

PAREMETER	SYMBOL	UNITS	NOMINAL VALUE
Rotor Speed	RPM	rev./min	18,000
Power Rating	P	watts	*
Voltage Rating (phase)	V_{ph}	volts (rms)	588
Number of Phases	n_{ϕ}	-	3
Number of Poles	p		14
Power Factor	PF	-	*
Rotor Tip Speed	V_t	ft/sec	600
Stator Bar Current Density	J_{cu}	amp/in^2	20,000
Peak Gap Flux Density	B	lines/in^2	50,000
Insulation Rating	VPMIL	volts/mil	80
Flux Density in the Yoke	B_{yoke}	lines/in^2	120,000
Stator Bar Packing Factor	F	-	0.80
Tooth Flux Density/B	α	-	2.5

*Depends upon the load.

(f) slot depth (see Figure 6(a))

$$d = \frac{C_s\ I_c}{(s-2\delta)\ F \times J_{cu}} + 0.01\ (C_s - 2) + 5\delta,\ \text{(inches)} \qquad (17)$$

where J_{cu} is the current density in the copper of the stator, δ is the ground wall insulation, $\delta = \sqrt{2}\ (V_{ph}/VPMIL) \times 1000$, and F is the stator conductor packing factor. If the cross-sectional area of a conductor were A_b, then the copper area is given by FA_b and the space reserved for cooling passages is given by $(1-F)A_b$.

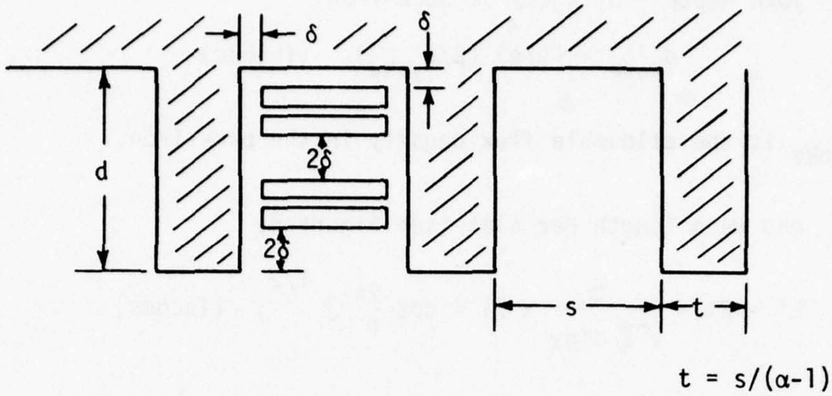

Figure 6(a). Slot Detail with Iron Teeth

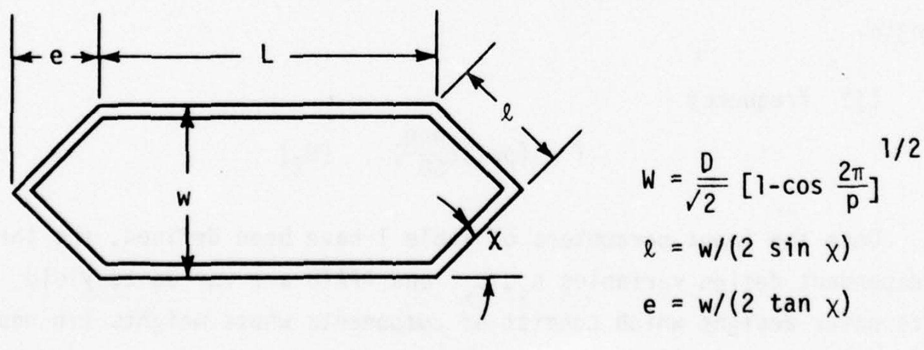

Figure 6(b). Stator Coil Geometry

Figure 6. Stator Winding Details for Iron-Core Alternators

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(g) yoke depth (thickness of back-iron)

$$d_{yoke} = (D/p)\ (B/B_{yoke}), \quad \text{(inches)} \tag{18}$$

where B_{yoke} is the allowable flux density in the back-iron.

(h) end turn length per slot (see Figure 4)

$$L' = 2\ell = \frac{D}{\sqrt{2}\ \sin\chi} \times \left[1 - \cos\frac{2\pi}{p}\right]^{1/2}, \quad \text{(inches)} \tag{19}$$

where the end turn extension angle, χ, is defined in Figure 6(b).

(i) stack length (straight length of the stator coils)

$$L = V_{ph}/[7.4018 \times 10^{-10} \times RPM \times K_W \times (n_s C_s/p) \times (p/PPATH) \times D \times B \times \left(\frac{C_s}{2}\right)^{-0.06546} \quad \text{(inches)} \tag{20}$$

where the factor $(C_s/2)^{-0.06456}$ accounts for slot leakage as the number of conductors per slot (or alternatively, the slot depth) is increased. This decreases the effective flux, B, and increases the required machine length.

(j) frequency

$$f = (p/2)\left(\frac{RPM}{60}\right) . \quad (H_Z) \tag{21}$$

Once the input parameters of Table 1 have been defined, the three independent design variables n_s, C_s, and PPATH are varied to yield alternator designs which consist of components whose weights (in pounds) are calculated by the following formulas:

(1) yoke (back-iron weight)

$$W_Y = \rho_Y\ [\Pi d_{yoke}\ (D + 2d + d_{yoke})]\ L, \tag{22}$$

(2) teeth

$$W_T = \rho_T \left[\frac{\pi D d}{\alpha} \right] L, \tag{23}$$

(3) stator insulation

$$W_{INS} = \rho_{INS} \times \text{SLOTS} \times (sd - C_s I_c / J_{cu})(L + 2L'), \tag{24}$$

(4) stator copper

$$W_{cu} = \rho_{cu} \times \text{SLOTS} \times (C_s I_c / J_{cu})(L + L'), \tag{25}$$

(5) rotor

$$W_R = \rho_R \, (\pi D^2/4) \, (1 - \xi^2) \, L, \tag{26}$$

where the mass densities, ρ_Y, ρ_T, etc, are in lbs/cu. in. Appendix B, and simply multiply the calculated component volumes. Overall machine weight is given by $(W_Y + W_T + W_{INS} + W_{cu} + W_R) \times 1.20$ and the "specific weight" in pounds per kilowatt can be found by dividing the overall machine weight by the power rating in kilowatts.

An algorithm for the volume of the generator can be derived once the machine dimensions have been determined. The envelope volume in cubic inches can be found by multiplying the overall machine length by the frame cross-sectional area, or

$$VOL = \pi \, (L + 2e) \, (D + 2d + 2d_{yoke} + 0.5)^2/4, \tag{27}$$

where e is the distance which the end turns extend beyond the straight portion of the coil (Figure 6(b)). A value of 0.5 inch is assumed to account for twice the air gap length plus twice the bore seal thickness. A bore seal is required on the stator inside diameter of machines which use fluid-cooled stators in order to exclude coolant from the air gap.

Appendix B includes a listing and sample output of a computer program written to calculate the weight and volume of a PMG. Parametric results obtained from the program are described in Paragraph 3.4.

In some cases, particularly for short run times, it may be desirable to design a generator without active cooling. Generators which operate in this adiabatic mode, where waste heat is absorbed by the heat capacities of the materials, are called "thermal lag" machines.

Thermal lag designs differ from actively cooled designs due to a reduction in the allowable stator conductor current density and an increase in F, the stator bar packing factor. For an operating time of Δt_{on} seconds and an average temperature rise of ΔT (°F), the current density can be obtained from the following equation:

$$J_{cu} \cong \sqrt{\frac{C_h \, \Delta T \, \rho_{cu}}{\Delta t_{on} \, \rho}} \quad , \text{(amp/in}^2\text{)} \qquad (28)$$

where $C_h \simeq 315$ joules/lb/°F is the heat capacity of copper, ρ_{cu} is 0.32 lbs/in.^{3}, and ρ is the electrical resistivity of copper, which can be calculated from

$$\rho = 6.77 \times 10^{-7} \times \left[\frac{234.5 + T}{254.5}\right] \quad , \text{(ohm-inches)} \qquad (29)$$

where T is in degrees centigrade. The average temperature rise is assumed to be about 1/4 of the allowable hot spot (or local) temperature excursion, which may be almost 400°F; therefore ΔT is assumed to be 100°F. The allowable operating stator conductor current density is only about 8,500 amp/in^2 for a 120 second run time. Another design consideration for thermal lag generators involves F. For actively cooled designs, about 20% of the conductor bar cross section is required for cooling passages, while 0% is required for thermal lag designs. Therefore, $F \simeq 0.8$ for an actively cooled generator, while $F = 1.0$ for a thermal machine.

3.3 GENERATOR EFFICIENCY CALCULATION

An estimate of generator efficiency is obtained by calculating the losses due to ohmic heating in the stator conductors and eddy current and hysteresis losses in the iron stator yoke and teeth. This approximation should be accurate to within 10%, since the rotor losses, including induced surface current losses, bearing and windage losses, are much less than the stator losses due to the large operating current densities in the stator bars, high operating frequency and relatively high magnetic flux densities in the iron.

Ohmic heating in the stator windings can be calculated from

$$P_{ohmic} = J_{cu}^2 \, \rho \, V_{cu} \text{ , (watts)} \tag{30}$$

where J_{cu} is the copper current density in amp/in^2, ρ is the electrical resistivity of copper defined in Equation 29 and $V_{cu} = W_{cu}/\rho_{cu}$ is the volume of stator copper in cubic inches.

Iron losses consist of hysteresis losses and eddy current losses given by

$$P_h = 7.1 \times 10^{-5} \, f \, B^{1.6} \quad \text{(watts/lb)} \tag{31}$$

and

$$P_c = 4.3 \times 10^{-9} \, f^2 \, B^2 \quad \text{(watts/lb)} \tag{32}$$

where f is the operating frequency and B is the peak magnetic flux density. Actual loss in the yoke or teeth can be calculated by multiplying the loss per pound by the weight of the yoke or teeth in pounds.

Generator efficiency is given by

$$\eta_G = \frac{P_{out}}{P_{out} + P_{loss}} \text{ ,} \tag{33}$$

where P_{out} is the generator output power in watts and P_{loss} is the sum of the ohmic losses and the iron losses.

3.4 COMPUTER PROGRAM PARAMETRIC RESULTS

To determine the accuracy of the computer program which utilizes the equations developed in Paragraph 3.2, the results obtained from the computer program are compared in Table 2 with an actual high power PMG design performed by AiResearch Manufacturing Company of California. The calculated specific weight of 0.104 lb/KW agrees with the design value, and the calculated volume is very close to the design value. Of course, all of the independent variable values and design parameters were chosen to be the same for both the computer program and the AiResearch design. This design can be considered as a "base-line case" with the parametric results described below obtained by varying the independent variables P (power), V_{ph} (phase voltage), or RPM (rotational speed) one at a time while keeping the other variables equal to their base value. In addition, parameters which depend upon the state-of-the-art, including J_{cu} (stator conductor current density) and V_t (rotor tip speed), are varied, in turn, from their base values while keeping the other variables at their base value.

Before describing the parametric results obtained from the computer program it is necessary to show that a fair comparison of generator weights and volumes for different values of the independent variables can be made only if the different designs have the same value of specific electric loading, in ampere-conductors per inch of stator periphery, given by

$$Q_L = \frac{n_s \cdot C_s \cdot p}{720 \cdot PPATH \cdot PF} \left[\frac{P\ (RPM)}{V_{ph} \cdot V_t} \right], \qquad (34)$$

Since the number of poles, p, and the load power factor, PF, are not varied in this study, the design parameters n_s, C_s, and PPATH must vary to yield designs with comparable specific loadings for different values of the independent variables in brackets. For example, if P were increased from 10 to 20 MW, the loading would double; however, if $n_s\ C_s$/PPATH were correspondingly halved, the loading would remain the same and a fair comparison of generator specific weight and volume for designs at the two power levels could then be made.

TABLE 2

BASE-LINE COMPARISON, 5 MW AIRESEARCH PERMANENT MAGNET GENERATOR

Design Parameters	AiResearch Design	PMG Program
Voltage (Volts, rms, line-line)	1018.5	1018.5
Power (MW)	5	5
RPM	18000.0	18000.0
No. of phases	3	3
No. of poles	14	14
Rotor tip speed (ft/sec)	625.50	625.50
Power factor	0.82	0.82
Armature current density (amp/in^2)	36,270	36,270
Peak gap density (lines/in^2)	48,900	47,400
Insulation rating (volts/mil)	100	100
Yoke flux density (lines/in^2)	100,000	100,000
Winding pitch	5/6	5/6
Ratio of tooth flux density to air gap flux density	2.2	2.2
No. of conductors per slot	2	2
No. slots/pole/phase	4	4
No. of slots in the stator	168	168
No. of parallel paths	14	14
Specific electric loading (ampere-conductors/inch)	3177	3120

TABLE 2 (CONTINUED)

Weights (lbs)	AiResearch Design	PMG Program
Total machine	520	522
Total machine (lb/kw)	0.104	0.104
Stator copper	26.2	24.8
Back iron (yoke)	64.6	65.5
Rotor	309.4	308.7
Dimensions (inches)	**AiResearch Design**	**PMG Program**
Stator coil end extension	1.01	1.06
Stack length	31.22	31.19
Stack OD	9.515	9.08
Rotor OD	7.96	7.96
Volume (cubic feet)	2.18	2.03
Aspect ratio (L/D)	3.92	3.92
Losses (Kilowatts)	**AiResearch Design**	**PMG Program**
Iron losses		
Back-iron (yoke)	27.8	27.9
Teeth	18.2	13.7
Ohmic losses	135.8	126.8
Efficiency (%), based on stator losses only	96.5	96.7

Specific electric loading is an indication of how hard a machine is being worked (or loaded). Higher specific loadings imply more power output per pound of machine weight as shown in Figure 7. The loading cannot be increased indefinitely because of cooling considerations. For advanced high-power permanent magnet generators, the specific electric loading is less than 3500. Note also in Figure 7 that for each value of loading, i.e., 1560, 2340, or 3120, the specific weight depends upon the particular combination of the two design parameters n_s, and C_s. The dependence is not strong, therefore n_s and C_s can be varied (to obtain the same value of loading) as the independent variables are changed and a fair comparison of generator weights and volumes can still be made.

In Figure 8(a), the specific weight and volume for high-power permanent magnet generator designs are shown as a function of rated output power. Note that the specific weight decreases even out to 20 MW; however, the decrease is much less for power levels above 5 MW. It is doubtful that generators above 10 MW can be constructed as single units because of manufacturing and assembly problems and extremely large aspect ratios. An approximate value for the aspect ratio (stack length divided by rotor OD) can be obtained from the following equation.

$$L/D \simeq 70 \frac{P\ (RPM^2)}{V_t^3\ K_W\ B\ Q_L\ PF} \tag{35}$$

Note from Figure 8(b) that the aspect ratio is approximately 4:1 at 5 MW and increases linearly with power, P, with the other parameters fixed at the base-line values. One way to reduce the aspect ratio is to increase the rotor tip speed; however, AiResearch has chosen 625.5 feet per second as a fairly conservative number which has been experimentally demonstrated. The approach taken by AiResearch is to design 5 MW machines as modules which are connected together in order to achieve higher power ratings. The same approach will be taken in this report with a 20% weight penalty and a 50% volume penalty imposed for interconnection as described in Section V. Note also in Figure 8(a) the very small volume of the PMG. A 5 MW machine occupies only 2 cubic feet of space.

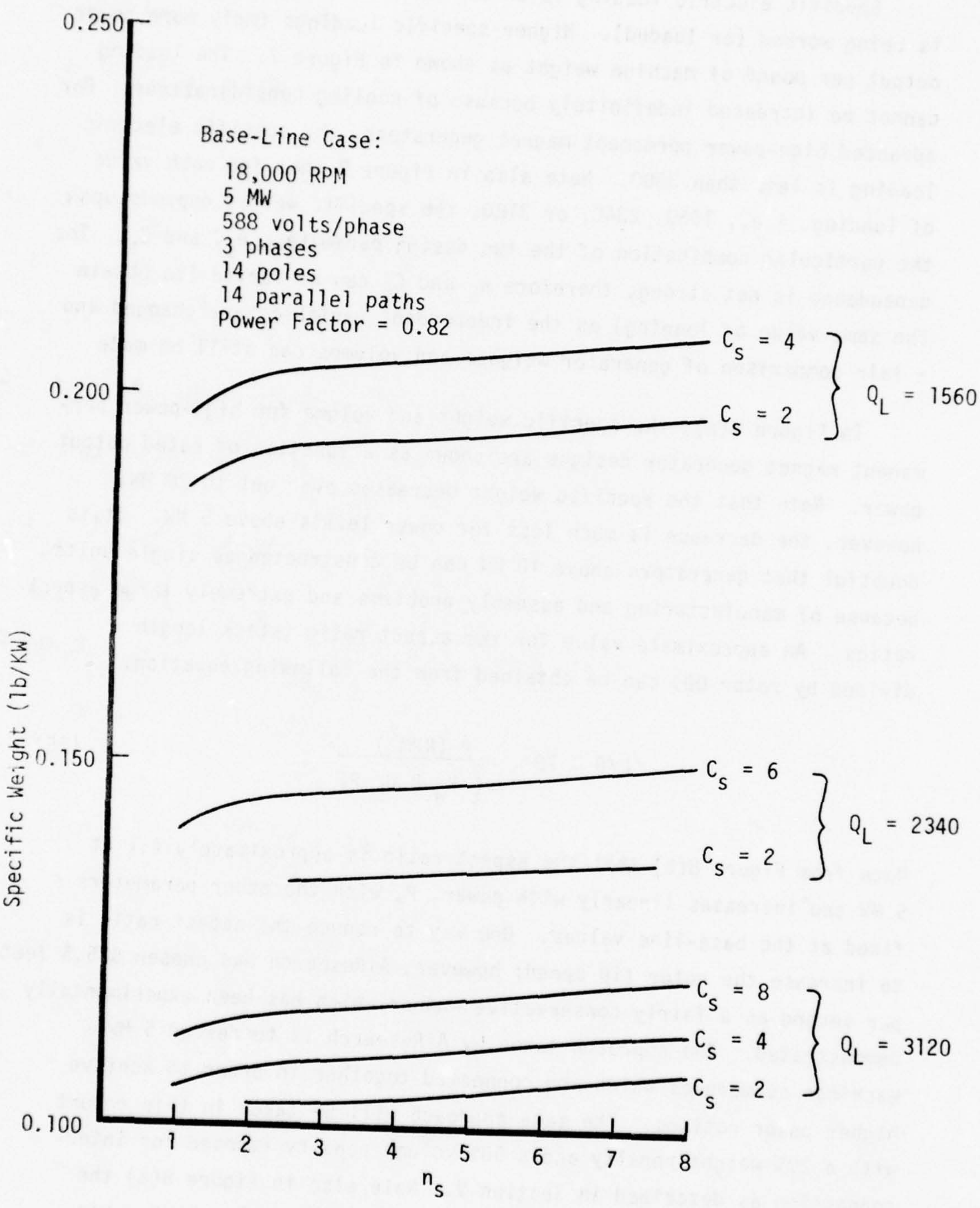


Figure 7. Base-Line Design Case for Different Specific Electric Loadings

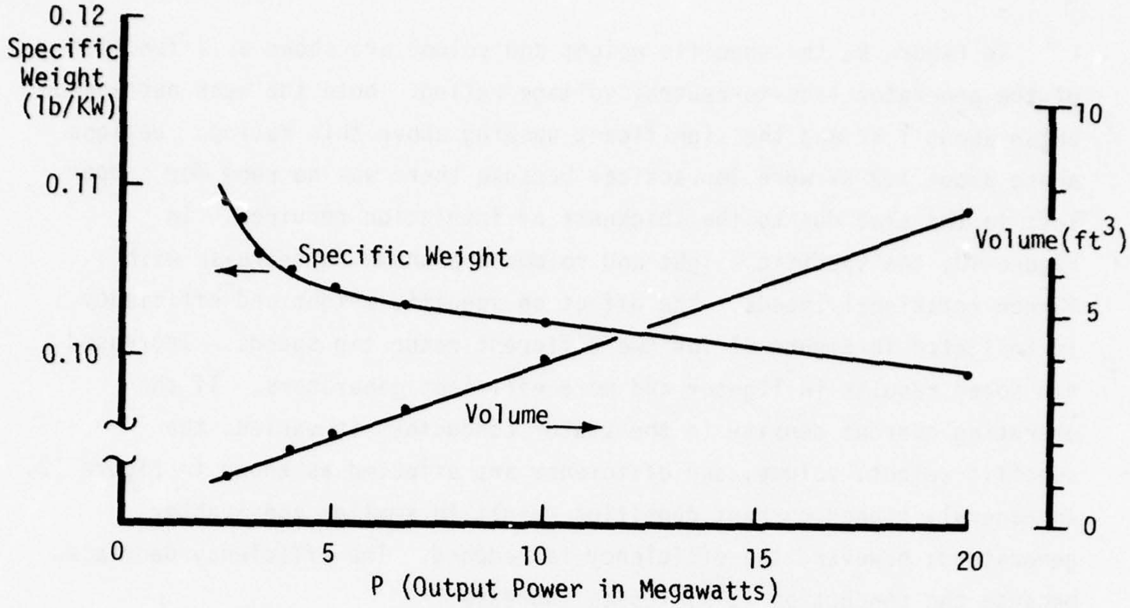


Figure 8(a). Specific Weight and Volume Versus Output Power

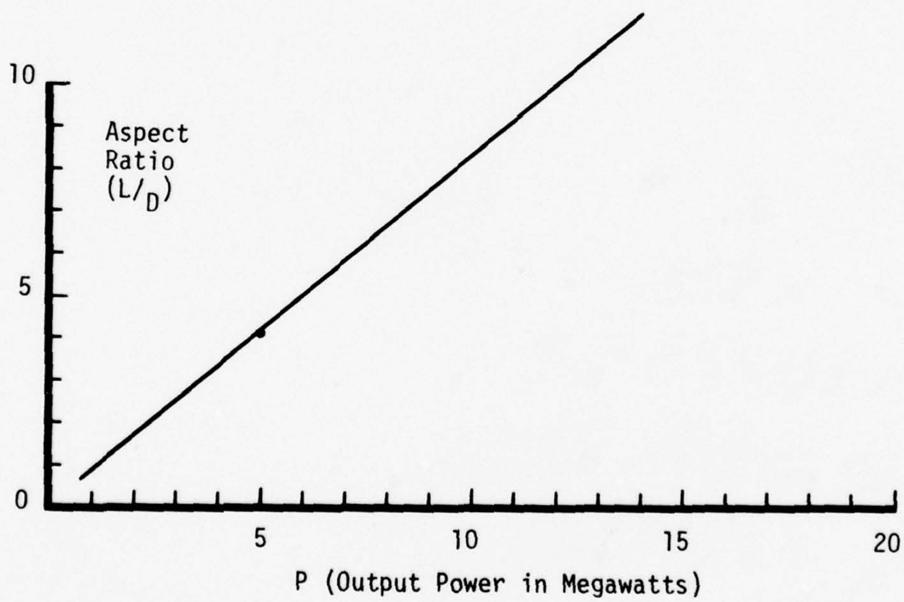


Figure 8(b). Aspect Ratio (L/D) Versus Output Power

Figure 8. PMG Output Power Variation

In Figure 9, the specific weight and volume are shown as a function of the generator line-to-neutral voltage rating. Note the weak dependence below about 1 KV and the significant upswing above this rating. Designs above about 1.2 KV were impractical because there was no room for copper left in the slot due to the thickness of insulation required. In Figure 10, the specific weight and volume are shown to decrease with larger rotational speeds. The effect on specific weight and efficiency is indicated in Figure 11 for two different rotor tip speeds. Increased tip speed results in lighter and more efficient generators. If the operating current density in the stator conductors is varied, the specific weight, volume, and efficiency are affected as shown in Figure 12. In general, higher current densities result in smaller and lighter generators; however, the efficiency is reduced. The efficiency decreases because the conduction (I^2R) losses increase.

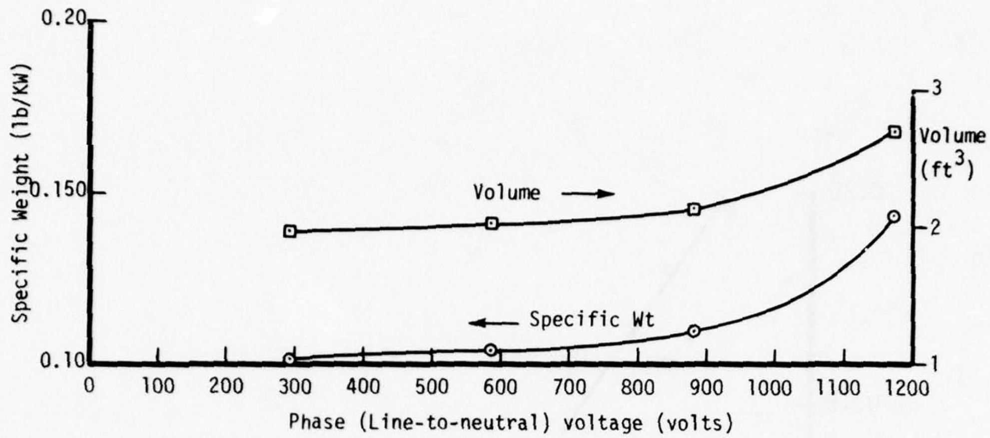


Figure 9. PMG Voltage Variation

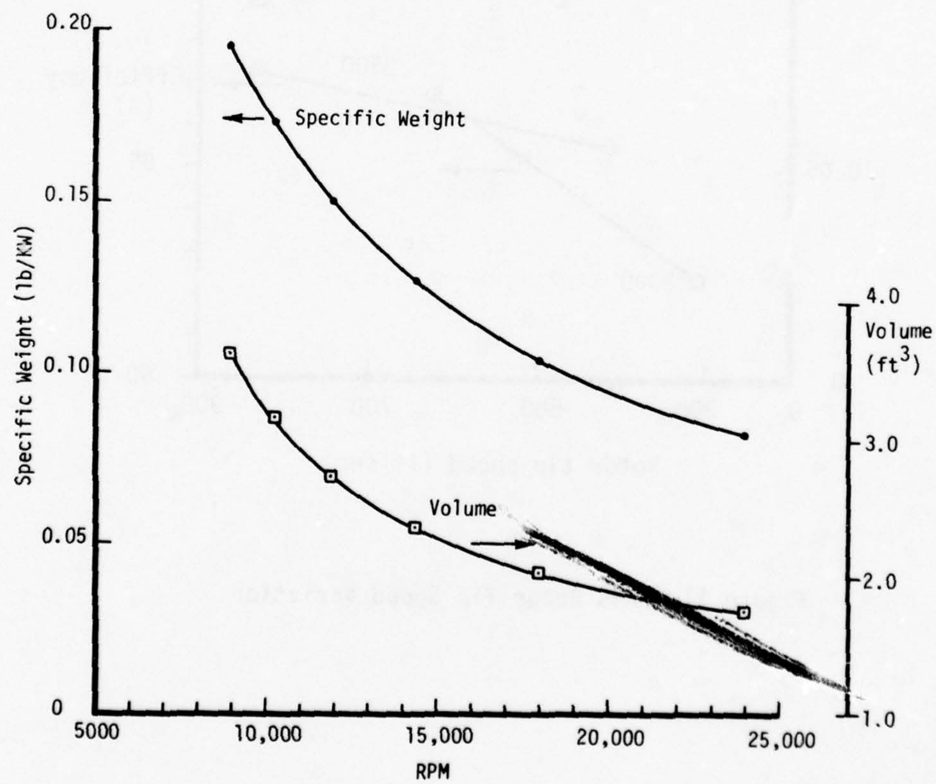


Figure 10. PMG RPM Variation

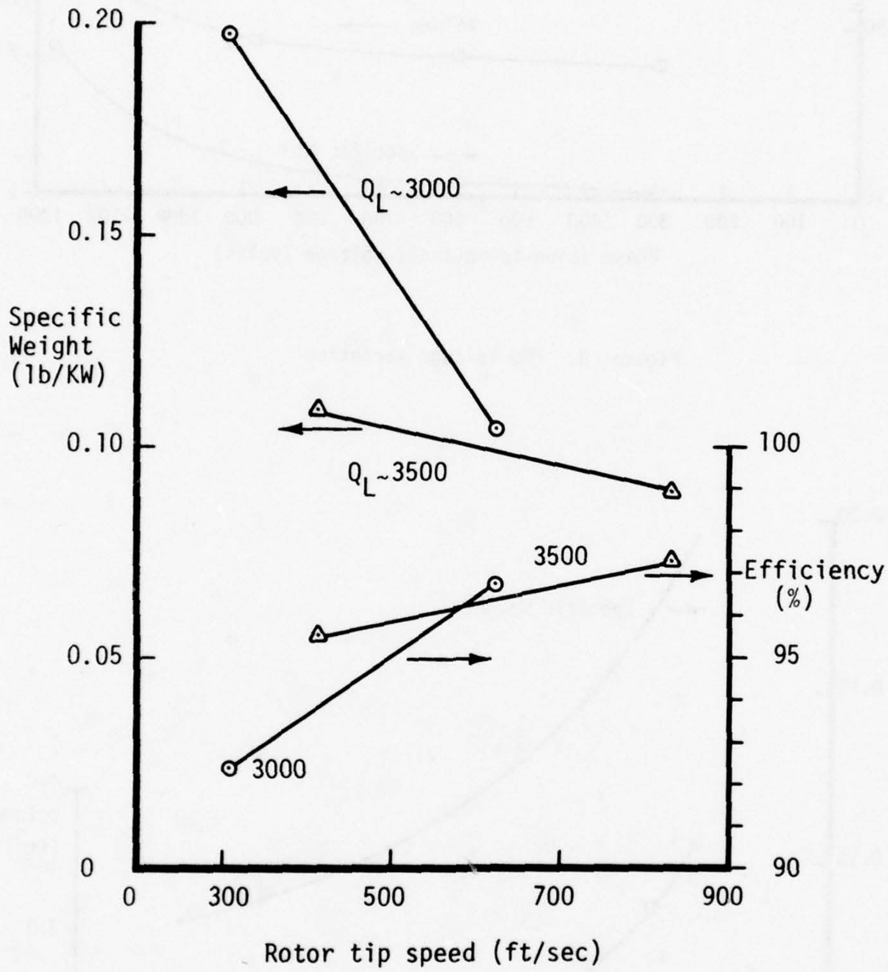


Figure 11. PMG Rotor Tip Speed Variation

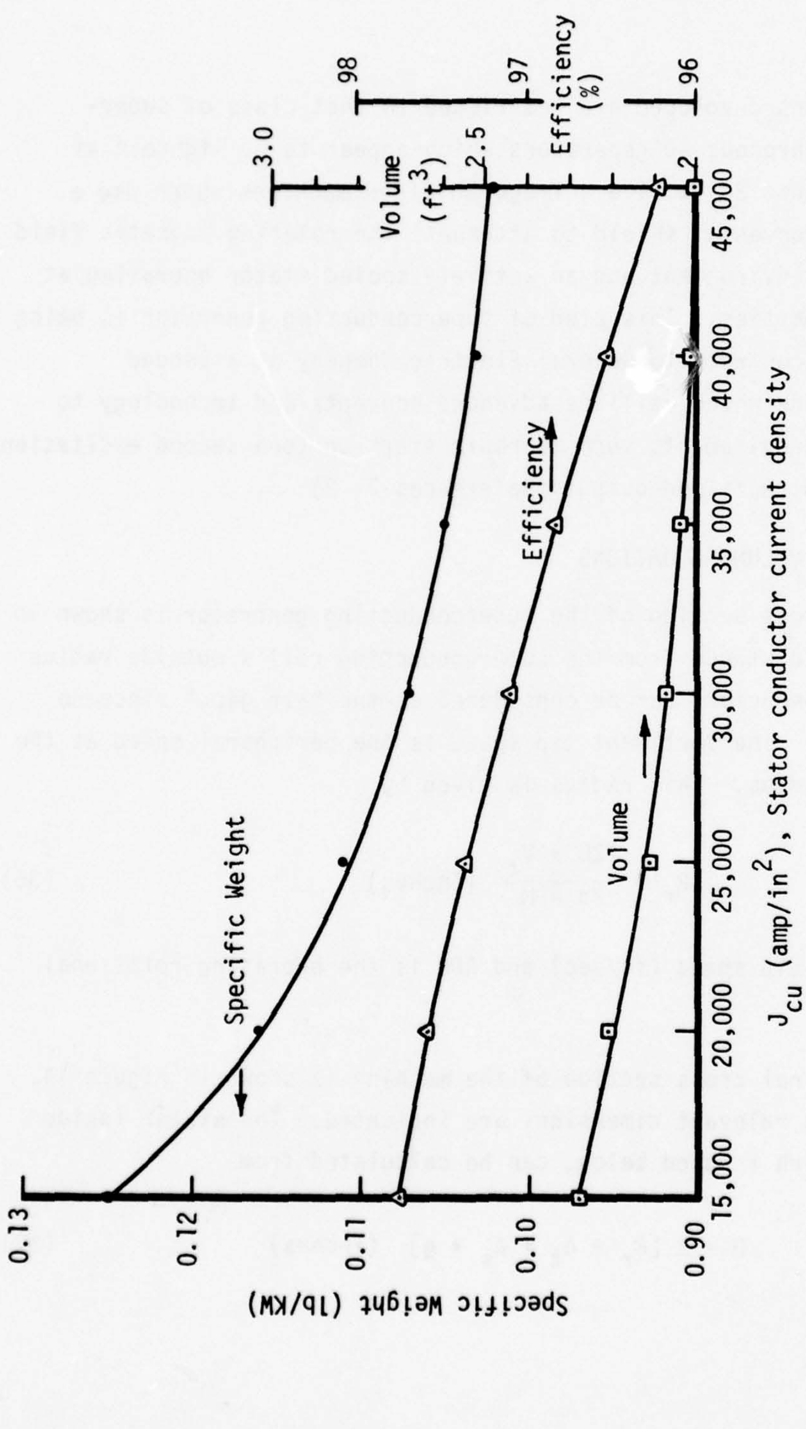


Figure 12. PMG Stator Current Density Variation

SECTION IV

SUPERCONDUCTING HIGH-POWER GENERATORS

4.1 BACKGROUND

The equations developed are restricted to that class of superconducting, synchronous AC generators which appear to be lightest at power levels around 20 MW, i.e., image-shielded machines which use a conductive environmental shield to attenuate the rotating magnetic field in the aircraft environment and an actively cooled stator operating at high current densities. This kind of superconducting generator is being developed under contract to General Electric Company as a second generation machine which utilizes advanced concepts and technology to operate within requirements such as rapid start-up (one second excitation and spin-up) and rectified output (References 7, 8).

4.2 WEIGHT AND VOLUME EQUATIONS

A radial cross section of the superconducting generator is shown in Figure 13. The distance from the superconducting coil's outside radius to the stator conductors can be considered as the "air gap," since no iron is present. The pertinent tip speed is the peripheral speed at the winding outer radius. This radius is given by

$$R_r = \frac{720 \times V_t}{2\pi \ \mathrm{RPM}} \quad \text{(inches)} \qquad (36)$$

where V_t is the tip speed (ft/sec) and RPM is the operating rotational speed.

A longitudinal cross section of the machine is shown in Figure 14, where all of the relevant dimensions are indicated. The stator inside diameter, D, which is used below, can be calculated from

$$D = 2\,[R_r + \Delta_t + \Delta_s + g] \quad \text{(inches)} \qquad (37)$$

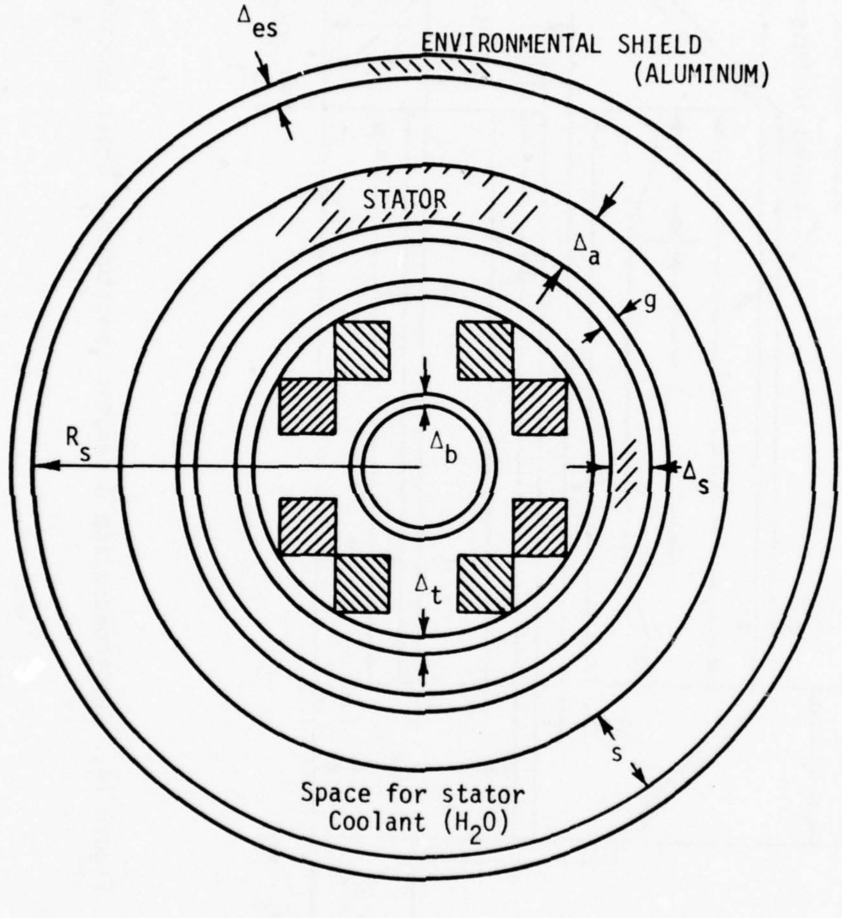


Figure 13. Superconducting Generator Radial Cross Section

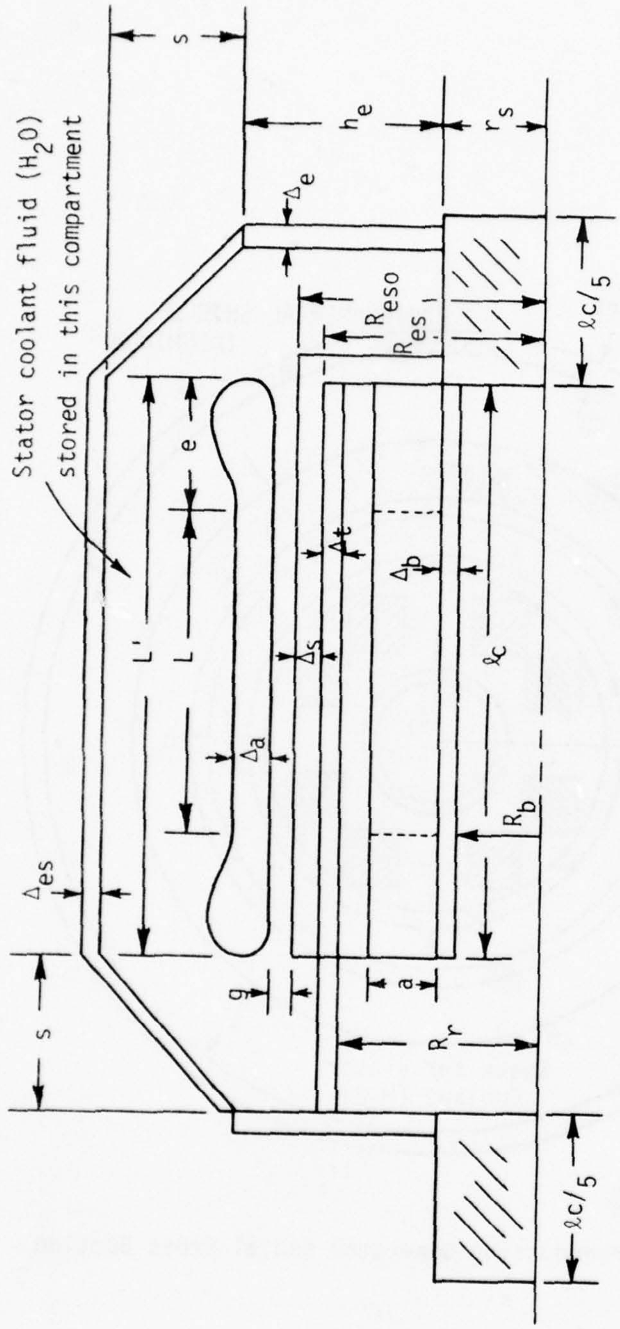


Figure 14. Superconducting Generator Longitudinal Cross Section

In this case, D cannot be assumed to be the same as D_r, i.e., $2R_r$, because of the large "air gap." It should be noted that there are no high permeability materials within the flux paths of this kind of machine; however, the superconducting field windings can easily supply the large mmf required by this low permeability path by virtue of the extremely large current densities in the superconducting field winding modules (96,774 amp/in^2).

The electromagnetic length of the stator can be obtained by using the voltage generation equation as in the previous section.

$$L_m = P/[7.50 \times 10^{-6} \times PF \times K_W \times RPM \times D^2 \times B_{kg} \times Q_L] \text{ (inches)} \quad (38)$$

The term B_{kg} is the average flux density (crest value) in Kilogauss in the stator winding calculated by taking an average of the two crest values at the stator winding ID and OD. This must be done since there are no iron teeth between stator bars in a superconducting generator, hence the permeability of the magnetic circuit is low and the magnetic flux density decreases rapidly across the winding. A subroutine is included as a part of the weight and volume algorithm which calculates flux densities based on the Biot-Savart law. Only four-pole, rectangular cross-sectional field coils can be handled at the present time. Specific electric loading Q_L, is the same term used in Section III; however, it is more convenient in the present context to express Q_L as

$$Q_L = \Delta_a F' J_{cu} \text{ (amp conductors per inch)} \quad (39)$$

where Δ_a is the winding thickness, F' is the armature (or stator) packing factor and J_{cu} is the copper current density. $F'J_{cu}$ is the armature overall annulus current density. In the computer program in Appendix B, F' is represented by the variable FARM and is a calculated quantity. The required length of the active conductor straight section is less than L_m because of emf generated in the end turns for this kind of machine. L, the actual straight section length, is given by the following equation, where L_m is assumed to be 25% longer than the actual length.

$$L = L_m/1.25 \text{ (inches)} \quad (40)$$

The stator coil geometry is identical to that in Figure 6(b) and the same geometrical relationships apply. However, a single layer stator winding is assumed as shown in Figure 15(a). A detail of a single bar (which occupies a single slot on the stator) is shown in Figure 15(b). The ratio of cross-sectional area of copper to the bar cross sectional area is the bar packing factor F_{bar}. A hollow, water-cooled conductor is indicated and the cross-sectional area of copper is just $C_s I_c / J_{cu}$, where C_s is the number of conductors per bar and I_c / J_{cu} is the cross-sectional area of a single conductor carrying a current of I_c amps with a current density in the copper of J_{cu} amps/in^2.

Racetrack-shaped coil modules are assumed for the superconducting field windings as indicated in Figure 16. Module dimensions depend upon D_r, p, and L. The independent dimensions of the module are its height, a, and bend radius, b. As shown in Figure 17, once a and b are specified, the module width can be calculated from

$$t = [(R_r - a \cos \pi/p) \times \sin \pi/p] - b \quad \text{(inches)} \qquad (41)$$

For the image-shielded machine, the skin depth in the environmental shield material at the operating frequency must be calculated. The frequency is given by Equation 21, and the skin depth by

$$\delta = \frac{1}{0.0254} \times \sqrt{\frac{2}{\omega \mu_o \sigma}} \quad \text{(inches)} \qquad (42)$$

where $\omega = 2\pi f$, $\mu_o = 4\pi \times 10^{-7}$ and σ is the conductivity of the shield material, which is about 3.77×10^7 mhos/m for aluminum. The environmental shield thickness, Δ_{es}, is assumed to be three times the skin depth for adequate attenuation of the electromagnetic field within the aircraft environment.

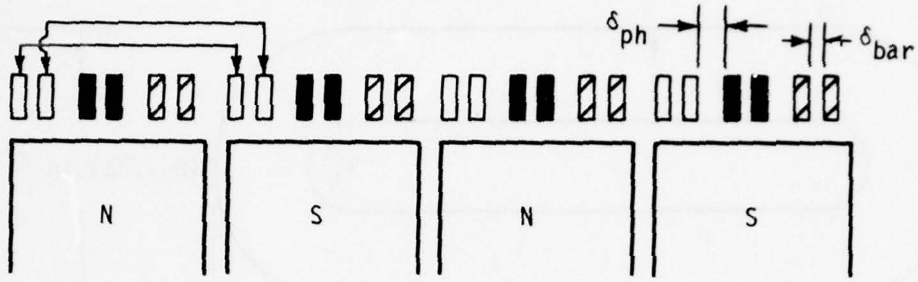


Figure 15(a). Single Layer Stator Winding (Developed View)

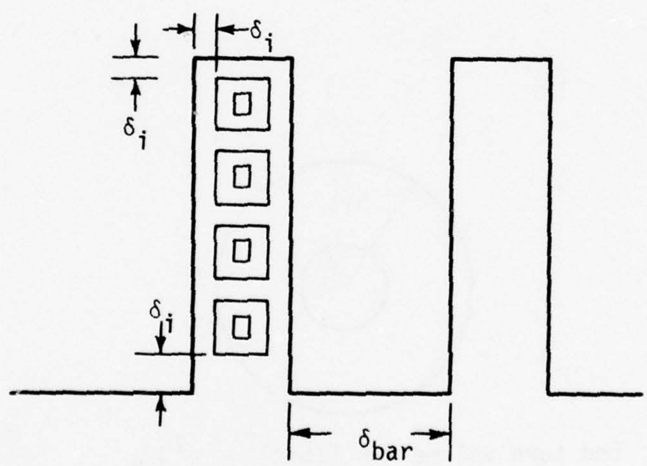


Figure 15(b). Stator Slot Detail

Figure 15. Stator Winding Details for an Air-Core Alternator

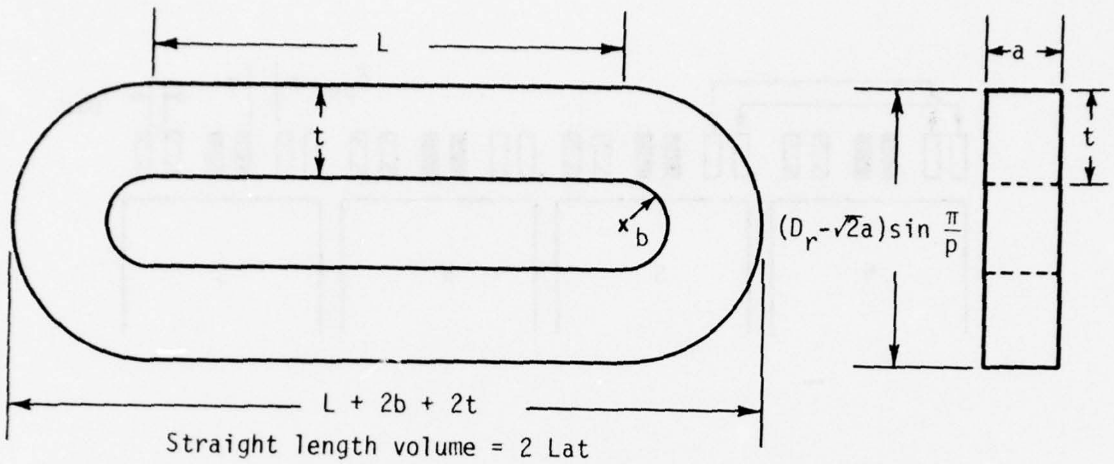
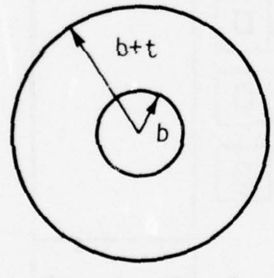


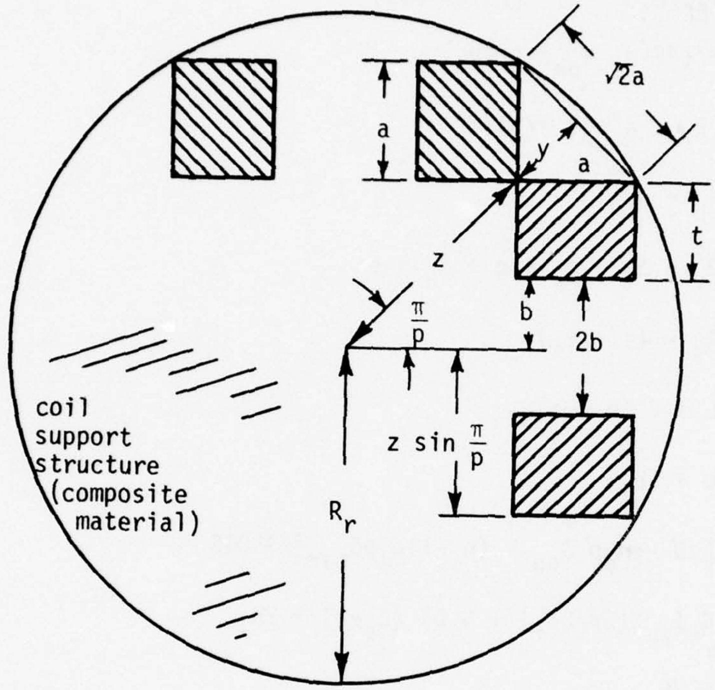
Figure 16(a). Rotor Field Coil Module Geometry



$$\text{End turn volume} = \pi\,[(b+t)^2 - b^2]\,a$$
$$= \pi\,[2bt + t^2]\,a$$

Figure 16(b). End Turn Volume of a Single Module

Figure 16. Rotor Field Winding Details for the Superconducting Generator



$$y = a \cos \pi/p$$

$$z \simeq R_r - a \cos \frac{\pi}{p}$$

$$t \simeq (z \sin \frac{\pi}{p}) - b$$

$$= [(R_r - a \cos \frac{\pi}{p}) \sin \frac{\pi}{p}] - b$$

Figure 17. Rotor Field Structure Arrangement Within the Coil Support Structure

The required input parameters are listed in Table 3. Intermediate parameters required to calculate component volumes are listed below with all dimensions in inches, unless otherwise indicated.

$$V_{ph} = V_{DC}/2.3 \qquad \text{(volts rms)} \tag{43}$$

$$I_{ph} = P/(PF\ n_{\phi}\ V_{ph}) \ \text{(amps)} \tag{44}$$

$$R_b = (R_r - a \cos \pi/p)/2 \tag{45}$$

$$r_s = R_b + \Delta_b \tag{46}$$

$$R_s = R_r + \Delta_t + \Delta_s + g + \Delta_a + s \tag{47}$$

$$h_e = R_s - (s + r_s) \tag{48}$$

$$L_c = L + 2\ (b + t) \tag{49}$$

$$L' = L + 2e \tag{50}$$

$$\text{SW(slot width)} = [\pi D - n_{\phi} p\ \delta_{ph} - (n_s - 1) n_{\phi} p \delta_{bar}]/\text{SLOTS} \tag{51}$$

$$\Delta_a = C_s I_{ph}/(SW - 2\delta_i) + 0.01\ (C_s - 1) + 2\delta_i \tag{52}$$

$$L_{de} = L_c/5 \tag{53}$$

$$L_{ade} = L_c/5 \tag{54}$$

$$Z = \pi D Q_L / I_{ph} \tag{55}$$

$$A_{cu} = I_{ph}/J_{cu} \quad (\text{amp/in}^2) \tag{56}$$

There are thirteen components for which volumes are calculated. Weights of the individual components are then determined by multiplying the component volumes by the corresponding mass densities shown in Table 8 in Appendix B.

TABLE 3

INPUT PARAMETERS REQUIRED FOR CALCULATING THE WEIGHT AND VOLUME OF A SUPERCONDUCTING GENERATOR

PARAMETER	SYMBOL	UNITS	NOMINAL VALUE
Power rating	P	Watts	20×10^6
Field winding tip speed	V_t	ft/sec	471
RPM	RPM	revolutions/min	6,000
Stator copper current density	J_{cu}	amp/in^2	33,000
Field winding current density	J_f	amp/cm^2	15,000
DC load voltage	V_{DC}	volts	40,000
Power factor	PF	--	0.86
Winding distribution factor	K_w	--	1.00
Stator bar packing factor	F_{bar}	--	0.45
Number of poles	p	--	4
Number of phases	n_ϕ	--	3
Coil bend radius	b	inches	1.50
Coil module height	a	inches	2.85
Stator coil end turn angle	χ	degrees	45
Gap between rotor and stator	g	inches	0.65
Distance from stator OD to environmental shield ID	s	inches	6.0
Damper shield thickness	Δ_s	inches	0.75
Phase break insulation	δ_{ph}	inches	0.50
Stator bar insulation	δ_{bar}	inches	0.02
Stator conductor insulation	δ_i	inches	0.005
Bore tube thickness	Δ_b	inches	0.25
Torque tube thickness	Δ_t	inches	0.60
End bell thickness	Δ_e	inches	0.50

Component volumes, in cubic inches, are given by the following equations:

(1) Environmental shield — cylindrical portion

$$V_1 = \pi L_c \times (2\Delta_{es} R_s + \Delta_{es}^2) \quad (57)$$

(2) Environmental shield — two conical sections

$$V_2 = 2\pi s \, \Delta_{es} \times (2R_s + \Delta_{es} - s) \quad (58)$$

(3) End Bells

$$V_3 = 2\pi \, \Delta_e \times [(R_s - s)^2 - r_s^2] \quad (59)$$

(4) Superconducting Winding Modules

$$V_4 = p \times [2Lat + \pi a \, (2bt + t^2)] \quad (60)$$

(5) Drive end-stub shaft plus bearings

$$V_s = \pi r_s^2 L_{de} \quad (61)$$

(6) Anti-drive end — helium transfer system plus bearings

$$V_6 = \pi r_s^2 L_{ade} \quad (62)$$

(7) Torque tube plus torque tube extension

$$V_7 = \pi(L_c + s) \, (2R_r \, \Delta_t + \Delta_t^2) \quad (63)$$

(8) Bore tube

$$V_8 = \pi L_c \, (2R_b \, \Delta_b + \Delta_b^2) \quad (64)$$

(9) Field winding support structure

$$V_9 = \pi L_c \, (R_r^2 - r_s^2) - V_4 \quad (65)$$

(10) Electromagnetic shield on the rotor (damper shield)

let $R_{es} = R_r + \Delta_t$ and $R_{eso} = R_{es} + \Delta_s$,

$$V_{10} = \pi L_c \, (R_{eso}^2 - R_{es}^2) + \pi\Delta_s (R_{eso}^2 - r_s^2) \quad (66)$$

(11) Copper in the stator

$$V_{11} = ZA_{cu} \, (L + W/\sin\chi) \tag{67}$$

(12) Insulation in the stator

let $R_i = R_{eso} + g$, and $R_o = R_i + \Delta_a$,

$$V_{12} = \pi L' \, (R_o^2 - R_i^2) - V_{11} \tag{68}$$

(13) Bore seal

$$V_{13} = \pi L' \, (2d_{BS} \times R_i + d_{BS}^2), \tag{69}$$

where d_{BS} is the bore seal thickness and is calculated in the program.

A computer program was written to calculate the volumes and the corresponding weights. The total weight of the machine is just the sum of the individual component weights. No correction factor is required to account for end bells, bearings, structure, etc., as in the PMG design, since everything is included in the component weights. An envelope volume which includes the cylindrical portion of the environmental image shield and the two end pieces which are frustums of cones is calculated from

$$\text{VOLUME} = \pi L' \, (R_s + \Delta_{es})^2 + 2\pi S[2R_s^2 + S^2 - 2SR_s + R_s(R_s - S)]. \text{ (cu/in)} \tag{70}$$

Appendix B includes a listing of the computer program and a sample output. Parametric results obtained from the program are described in Paragraph 4.4.

4.3 GENERATOR EFFICIENCY CALCULATION

An estimate of the efficiency for the superconducting generator can be obtained by calculating the ohmic (I^2R) losses in the normally conducting copper stator bars, the eddy current losses in the stator bars, and the losses due to surface currents induced on the environmental image shield. Even though windage, bearing, and rotor (electromagnetic shield) losses are not considered, they are small compared to the above losses, and a reasonably accurate estimate of efficiency should be obtained.

Ohmic losses are determined by

$$P_{ohmic} = J^2_{cu}\rho_c V_{11} \quad \text{(watts)} \tag{71}$$

where J_{cu} is the current density in the stator in amperes/m^2, ρ_c is the resistivity of the conductors, assumed to be copper, given by

$$\rho_c = 1.72 \times 10^{-8} \left[\frac{234.5 + T}{254.5}\right] \quad \text{(ohm-meters)} \tag{72}$$

where T is the average stator bar conductor temperature in degrees centigrade and V_{11} is the volume of copper in the stator given by Equation 67, expressed in m^3.

Since the full magnetic field is allowed to penetrate the copper stator bars rather than being shunted through iron teeth around the bars as in conventional, iron-core machines, the eddy current losses are significant. For square, hollow conductors as shown in Figure 15b, the eddy current loss in watts is given by (Reference 12)

$$P_{eddy} = \frac{\omega^2}{24\rho_c}\left[\frac{h_o^4 - h_i^4}{h_o^2 - h_i^2}\right] \times [B^2_{\theta m} + B^2_{rm}] \times Z \times A_{cu} \times L_c \, , \tag{73}$$

where ω is the electrical radian frequency, h_o is the conductor height in meters, t_i is the width of the hollow center of the conductor in meters, $B_{\theta m}$ is the average of the peak value of the azimuthal components of magnetic flux density calculated at the inner and outer radii of the stator, and B_{rm} is the average of the radial component. $B_{\theta m}$ and B_{rm} are in Tesla$_V$ and A_{cu} and L_c must be in meters.

Losses due to induced surface currents on the environmental shield are calculated from

$$P_{shield} = \frac{\pi R_s L'}{\sigma\delta} \times \frac{B^2_{tan}}{\mu_o^2} \, , \text{(watts)} \tag{74}$$

where R_s is the radius of the environmental shield (in meters), $L' = L+2e$ (in meters) and B_{tan} is the crest value of the azimuthal component of the magnetic flux density at radius R_s in Tesla. The skin depth, δ, must be expressed in meters. Shield losses predicted from this equation are almost 50% lower than the losses predicted by the GE design as shown in Table 4.

Generator efficiency is calculated from

$$\eta_G = \frac{P_{out}}{P_{out} + P_{loss}} , \tag{75}$$

where P_{out} is the electrical power output and P_{loss} is equal to the sum of the stator losses and the losses in the environmental shield.

4.4 COMPUTER PROGRAM PARAMETRIC RESULTS

To determine the accuracy of the computer program which implements the weight and volume equations given in Paragraph 4.2, predicted machine parameters from the program are compared in Table 4 with an actual superconducting generator design produced by General Electric Company (Reference 8). As shown in Table 4, the predicted weight and volume agree well with the GE design numbers for identical input parameters. This design point is considered the "base-line design" and parametric results are obtained by varying certain input parameters from their base values, indicated in Table 4.

Parametric results are obtained for the independent variables P (output power rating), DC rectified output voltage, and RPM. In addition, the technological parameters J_{cu} (stator conductor current density) and J_f (field winding current density) are varied from the base-line design. As described in the beginning of Paragraph 3.4, all designs must be compared on an equal specific electric loading basis. This has been done in the following curves which illustrate how the weight, volume, and efficiency of this class of superconducting generators change with rating and other machine input parameters.

TABLE 4

BASELINE COMPARISON, 20 MW GE SUPERCONDUCTING GENERATOR

Design Parameter	GE Design	SCGEN Computer Program
Voltage (volts rms, line-line)	30,100	30,100
Rectified DC Output Voltage (KV)	40	40
Power (MW)	20	20
RPM	6,000	6,000
No. of phases	3	3
No. of poles	4	4
Field winding tip speed (ft/sec)	471	471
Power factor	0.86	0.86
Armature current density ($amp.in^2$)	29,400	29,400
EM shield thickness (in.)	0.75	0.75
Torque tube thickness (in.)	0.50	0.50
Armature annulus packing factor	0.386	0.386 (calculated)
Field winding module overall current density (amp/cm^2)	15,000	15,000
Specific electric loading (ampere-conductor/inch)	11,400	13,692 (calculated)
Slots/pole/phase	28	28
Conductors/slot	6	6
No. of parallel paths	1	1
No. of slots	336	336

TABLE 4 (CONTINUED)

Weights (lbs)	GE Design	SCGEN Program
Total machine	1740	1706
Total machine (lb/KW)	0.087	0.085
Rotor	870	846
Armature copper	286	274
Environmental shield	280	285
Stator bore seal	32	39
EM shield	112	85
Field winding modules	246	258

Dimensions (in.)	GE Design	SCGEN Program
Field winding outer radius	9.0	9.0
Armature thickness	1.0	1.42
Straight length of coils	6.0	5.0
Thickness of environmental shield	0.50	0.69
Radius of environmental shield	19.7	19.1
Volume (cubic feet)	35	35

Losses (KW)	GE Design	SCGEN Program
Ohmic losses	770	756
Armature eddy current	390	347
Environmental shield	380	193
Efficiency (%), based on stator losses only	93	93.9

Magnetic fields (kilogauss)	GE Design	SCGEN Program
Radial flux density at:		
armature inner radius	14.0	17.3
armature outer radius	9.9	11.6

In Figure 18, the specific weight, volume, and efficiency are shown as a function of rated output power. The efficiency of this class of generators is comparable to the PMG only at power levels above 50 MW. Also, the volume is approximately three times as great as the volume of a PMG of similar power rating.

The dependence of specific weight, volume, and efficiency upon the generator output voltage is indicated in Figure 19. Phase voltage (rms) is approximately one half the DC rectified output voltage. Note that even for an output voltage of 100 KV DC the specific weight increases by only 50% above the base-line design at 40KV, and the volume by only 27%. This is in direct contrast to the PMG where voltages of even a few KV were unattainable. This high voltage capability of the superconducting generator is due to the "air-core" nature of the stator winding and consequently the extra space for insulation in the absence of iron teeth. It is concluded, therefore, that the PMG is a "low voltage" generator while the superconducting generator is a "high voltage" generator. Efficiency is only a weak function of output voltage as shown in Figure 19.

The effect of rotational speed variation is shown in Figure 20. Note that there is a minimum in the specific weight and volume curves at about 8000 RPM and a peak in the efficiency curve at about the same speed.

The current density in the field winding coils is determined by the characteristics and packing factor of the superconducting wire or cable used in winding the coils. This parameter is, therefore, set by current technology and/or manufacturing limits. For the base-line design, the current density is 15,000 amps/cm^2 (i.e., 96,774 amp/in^2). In Figure 21, the generator specific weight, volume and efficiency are shown as a function of field winding current density. Specific weight and volume decrease slowly as the field winding current density is increased. Note that the efficiency also decreases. This offsets the advantage of reduced weight and volume to some degree. The decrease in efficiency is due to increased eddy current losses in the stator winding and environmental shield.

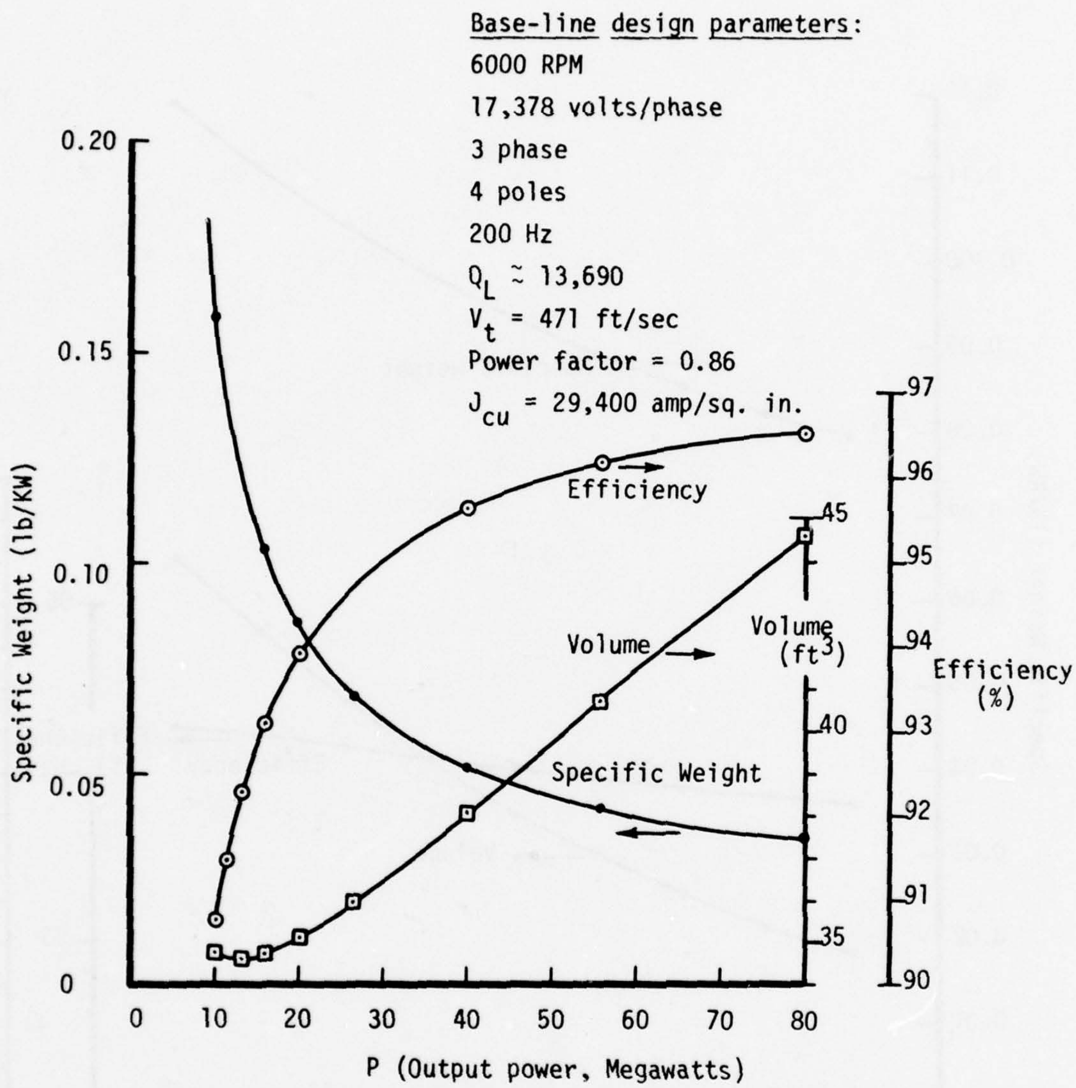


Figure 18. Superconducting Generator Output Power Variation

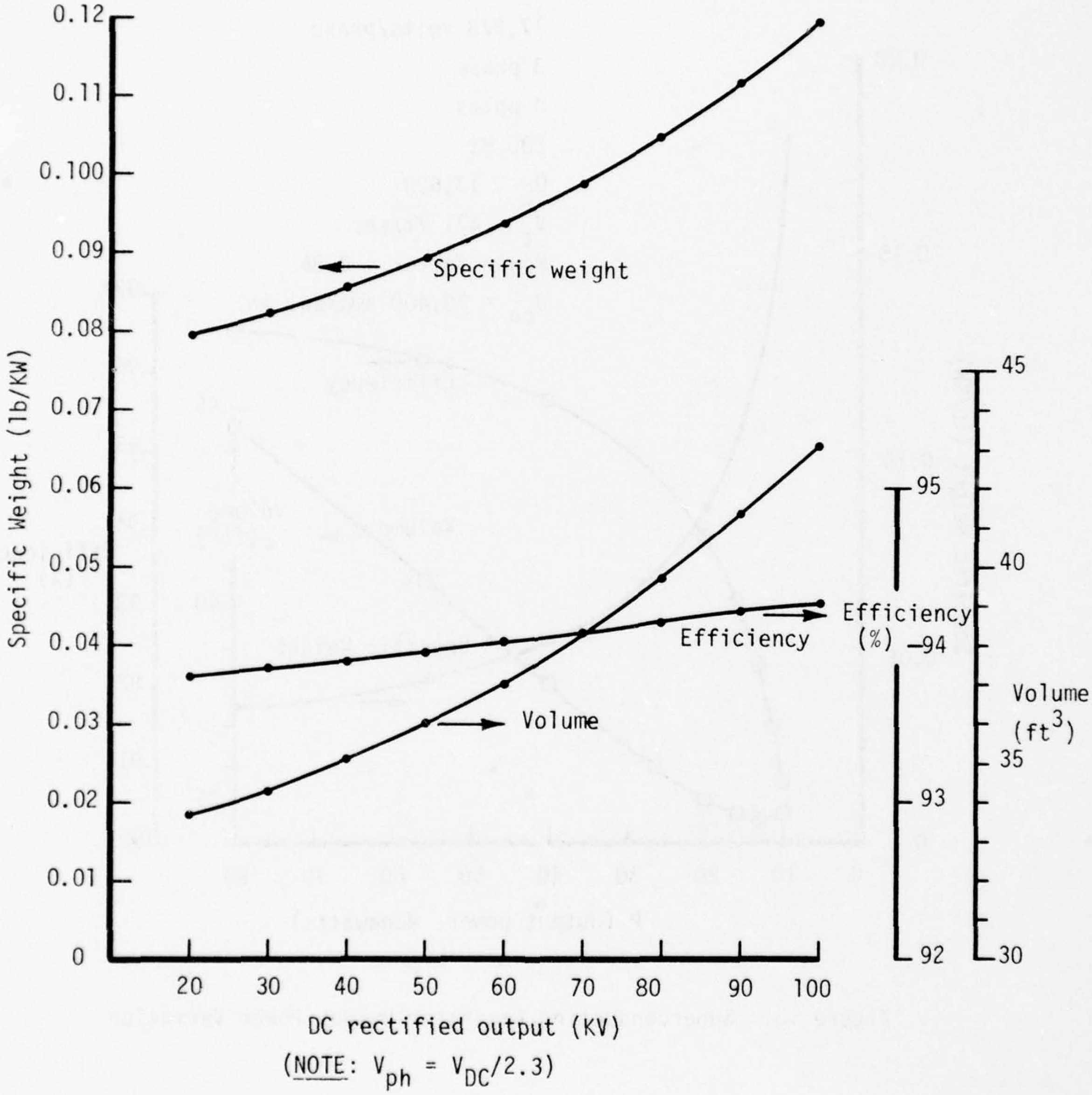


Figure 19. Superconducting Generator Voltage Variation

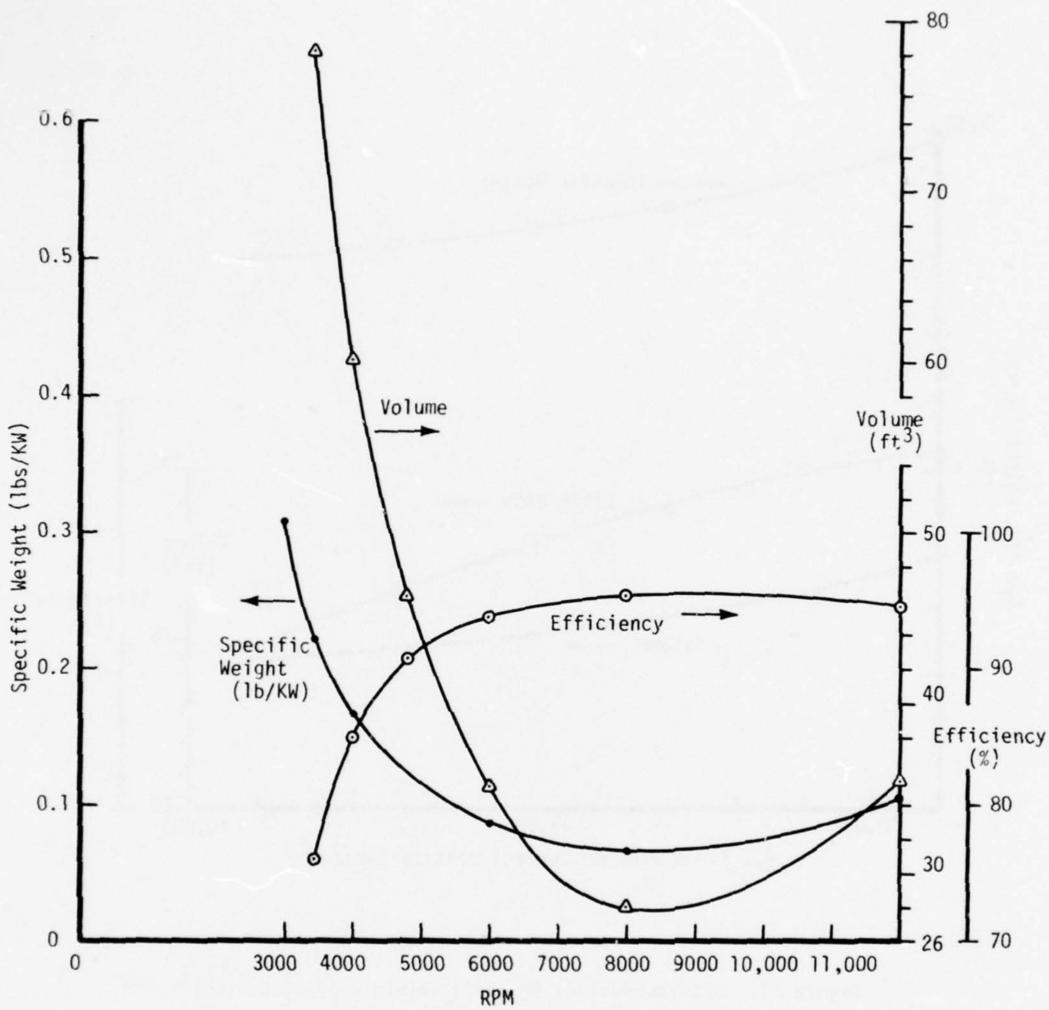


Figure 20. Superconducting Generator RPM Variation

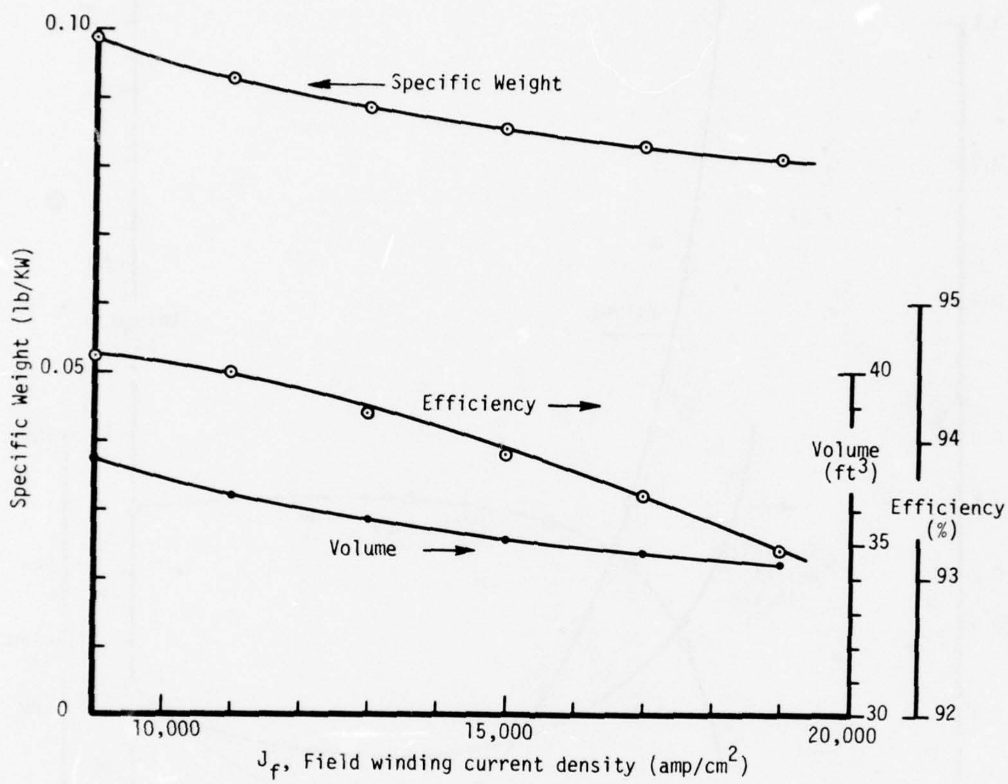


Figure 21. Superconducting Generator Field Winding Current Density Variation

In Figure 22, generator specific weight, volume, and efficiency are plotted as a function of the current density in the stator conductors. Again, all three parameters decrease for increasing current density; however, the rate of decrease of both weight and volume is greater than that observed when the field winding current density was varied. Decreasing efficiency is caused by the larger conduction (I^2R) losses in the stator conductors.

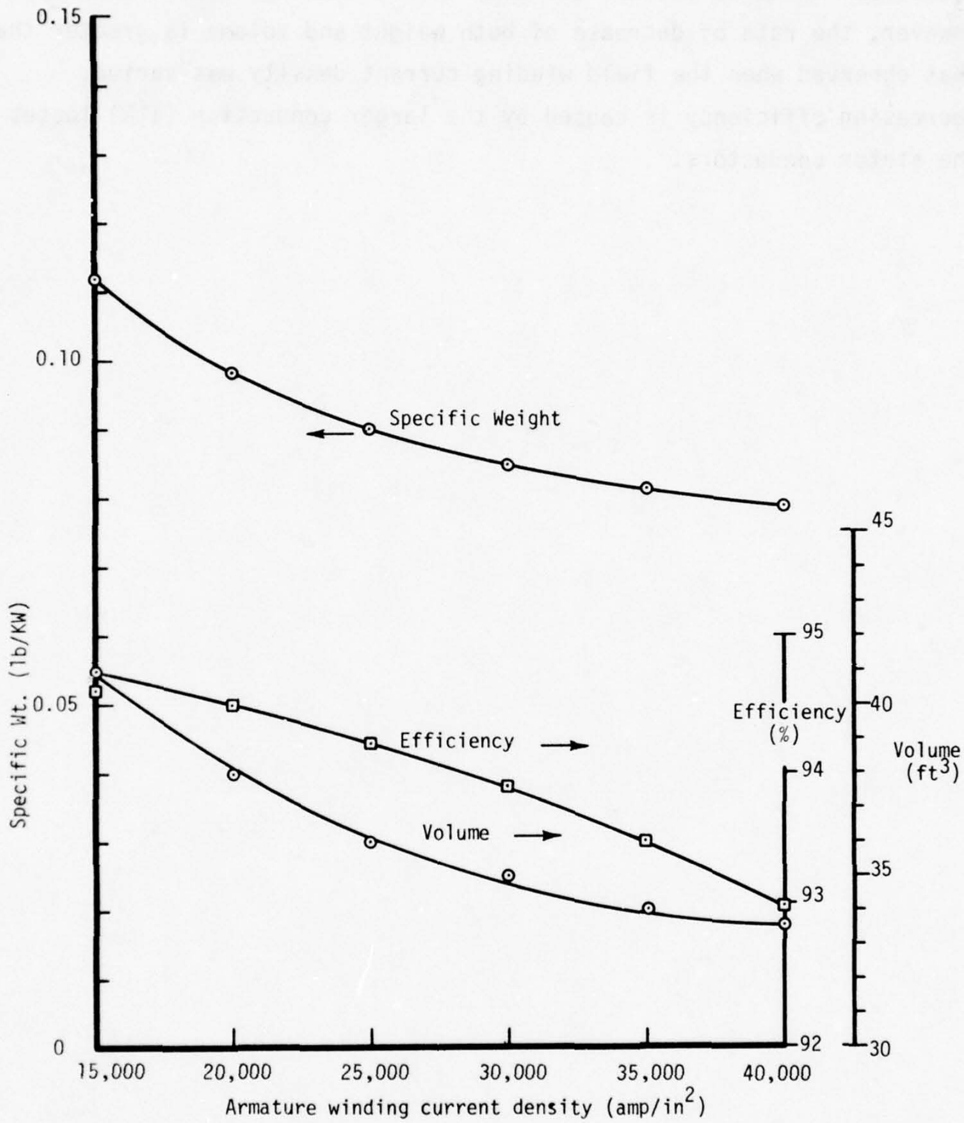


Figure 22. Superconducting Generator Stator Conductor Current Density Variation

SECTION V

GENERATOR INFLUENCE ON POWER SYSTEM WEIGHT

A true comparison of different generator concepts, such as permanent magnet and superconducting, can only be made by comparing complete power supply systems. Even though one generator may weigh less than another generator for the same power output, the overall system which uses the lighter generator as a component may be appreciably heavier because of the influence that the generator has upon the system. The mechanical part of the system is influenced by the generator (rotor) rotational speed and the generator efficiency. The cooling subsystem is also affected by generator efficiency. Components in the electrical part of the system (power conditioning subsystem) are influenced by the generator frequency and output voltage.

Therefore, to compare the PMG and the superconducting generator, system weights were calculated by using the algorithms described in Appendix C (Reference 13) and the two generator algorithms in Appendix B. The systems are shown in block diagram form in Figure 23 for the PMG and Figure 24 for the superconducting generator. A total power generation time (or run time) of 120 seconds is assumed. The auxiliary mechanical power is assumed to be zero for simplicity and a main transformer (T1) is not required for the system in Figure 24 because of the high voltage capability of the superconducting generator. The assumed component efficiencies are indicated below each component. Note that the efficiency for the power conditioning component includes the efficiencies of both a rectifier and an LC filter. Power levels shown in parentheses are for a 20 MW (approximately) generator and the other power levels correspond to a 10 MW (approximately) generator. The load consists of a main power of 6 MW or 15 MW at 30 KV DC or 40 KV DC, respectively, and a secondary power of 1 MW or 2 MW at 130 KV DC or 150 KV DC, respectively. Numbers in circles near the gear box indicate point designs which use a gear box or direct drive between the turbine and the alternator.

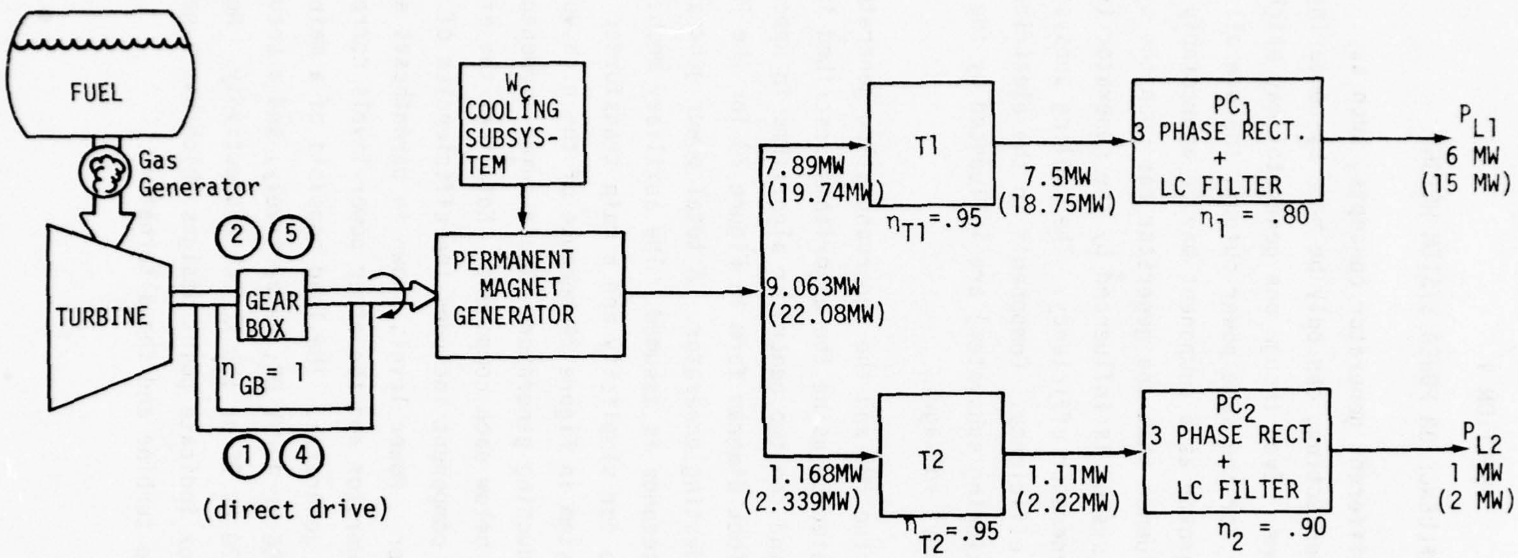


Figure 23. PMG System Block Diagram for the Point Designs

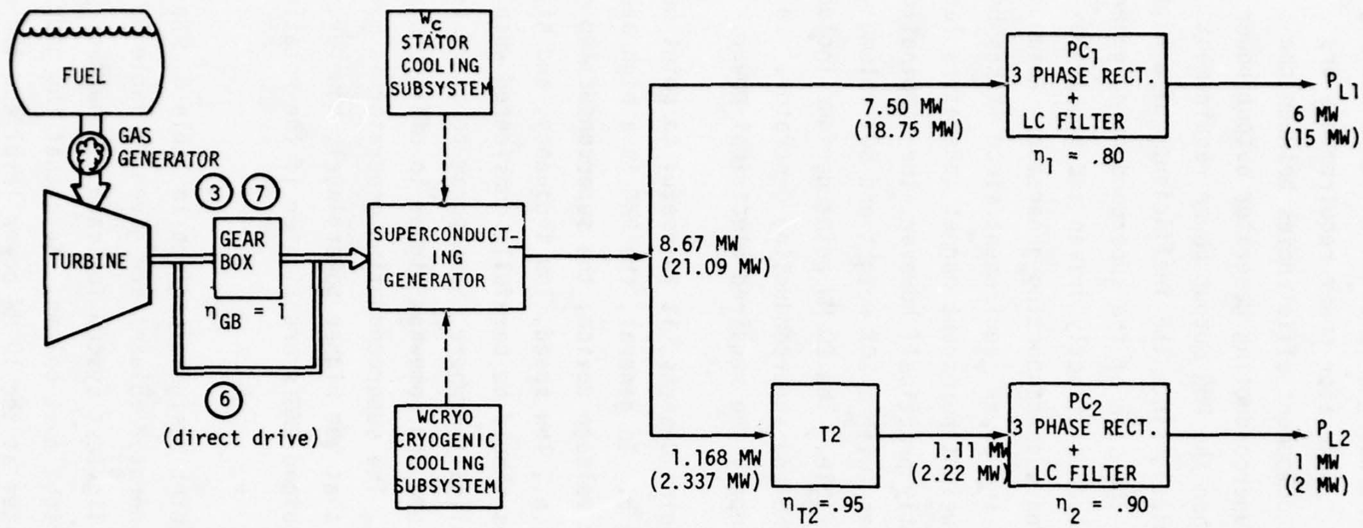


Figure 24. Superconducting Generator System Block Diagram for the Point Designs

A summary of the seven point designs is shown in Table 5 along with the two base-line designs. Generator power requirements are determined by the load and the component efficiencies between the generator and the load. The superconducting generator output power of 8.670 MW is slightly less than the PMG output power requirement of 9.066 MW (two 4.533 MW modules), since the inefficiency of a high power transformer is absent in the case of the superconducting generator system. The 10 MW designs include a directly driven and a gear box driven PMG and a gear box driven superconducting generator. Note that two PMG's must be used to meet the power requirement since it has been assumed that single unit lightweight permanent magnet generators larger than about 5 MW are not presently practical; however, the combination of any number of these size devices (with a 20% weight and 50% volume penalty for connection) is feasible. The 20 MW point designs include a direct and gear box driven PMG and superconducting generator. In this case, four PMG's are used to supply the required electrical power.

Before comparing system point designs, it is useful to point out a few items of interest in Table 5. In general, the PMG is a high speed, high frequency, and low output voltage device; the superconducting generator is just the opposite, i.e., low speed, low frequency, and high output voltage. These features should be carefully considered when selecting a machine for an application where these parameters are critical. The PMG is much smaller in volume and somewhat higher in efficiency than the superconducting generator. The superconducting generator is much lighter than the combined PMG's at the higher power level; however, at the lower power level, the combined PMG's are lighter if the rotational speed is high enough.

A summary of the system point designs is given in Table 6. No volumes are given; however, generator volumes are given in Table 5. System weight relative to the lightest system for each of the two power levels is shown in the right most column. Note that the gear box driven PMG is the lightest system at the 10 MW power level and the directly driven superconducting generator is the lightest system at the 20 MW power level.

TABLE 5

SUMMARY OF GENERATOR POINT DESIGNS

POINT DESIGN NUMBER	GENERATOR POWER (MW)	RPM rev/min	VOLTAGE DC KV	WEIGHT (lbs)	VOLUME (ft^3)	η_G %	f KHz
1 PMG	4.533	14,900	1.376	720	2.68	96.66	1.738
2 PMG	4.533	18,000	1.376	516	2.01	96.69	2.10
3 S/C Gen.	8.67	6,000	30	1357	31.4	91.64	0.20
4 PMG	5.52	10,500	1.376	832	3.04	96.66	1.225
5 PMG	5.52	18,000	1.376	530	2.05	96.79	2.10
6 S/C Gen.	21.09	10,500	40	1636	30.5	94.39	0.35
7 S/C Gen.	21.09	6,000	40	1732	35.4	93.97	0.20
Base line (PMG)	5.0	18,000	1.376	522	2.03	96.74	2.1
Base line (S/C Gen.)	20.0	6,000	40	1706	35.1	93.91	0.20

TABLE 6

SUMMARY OF SYSTEM POINT DESIGNS
(COMPONENT WEIGHTS, POUNDS)

	POINT DESIGN	FUEL	TURBINE	GEAR BOX	COOLING SUBSYSTEM	GENERATOR	POWER CONDITIONING	SYSTEM	RELATIVE WEIGHT
10 MW:									
	1 (PMG)	2934	770	0	301	1728	643	6,376	1.074
	2 (PMG)	2933	770	182	301	1238	513	5,937	1.000
	3 (SCG)	2960	770	484	334	1357	828	6,733	1.134
20 MW:	4 (PMG)	7146	1760	0	419	3994	1376	14,695	1.243
	5 (PMG)	7136	1760	507	419	2544	1043	13,409	1.134
	6 (SCG)	6989	1760	0	450	1636	988	11,823	1.000
	7 (SCG)	7021	1760	1156	461	1732	1399	13,529	1.144

Plots of component weights in Figures 25 and 26 enable one to more easily see how the weight distribution within the system changes as the generator design changes. Note that the fuel weight dominates at both power levels. A 14,900 RPM turbine using JP4-LOX fuel with a specific propellant consumption (SPC) of 7.0 lbs/(horsepower-hr) is used for the 10 MW power level, and a 10,500 RPM turbine using JP4-LOX fuel with an SPC of 7.0 lbs/(horsepower-hr) is used for the 20 MW power level.

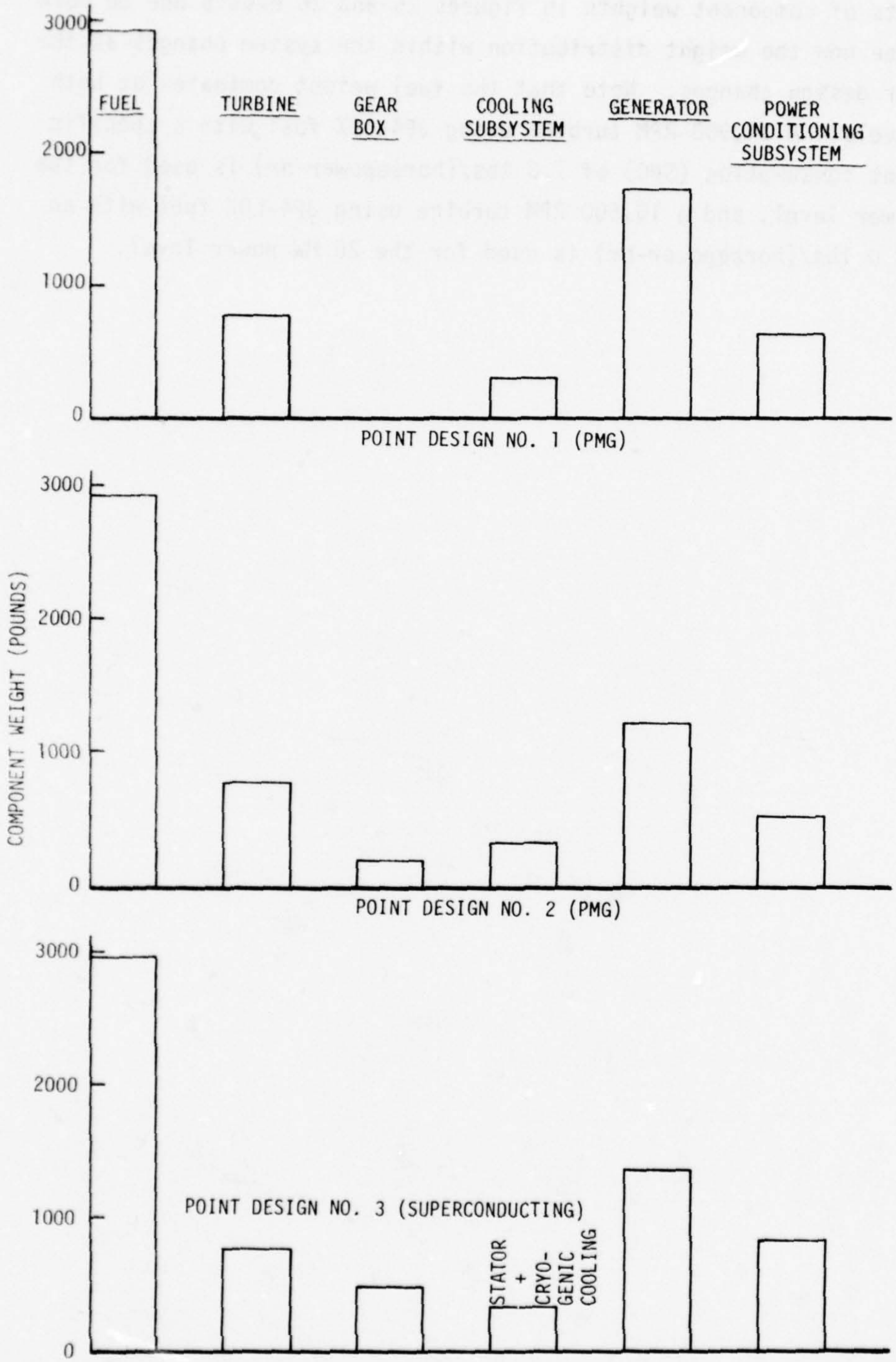


Figure 25. System Weight Distributions for the 10 MW Point Designs

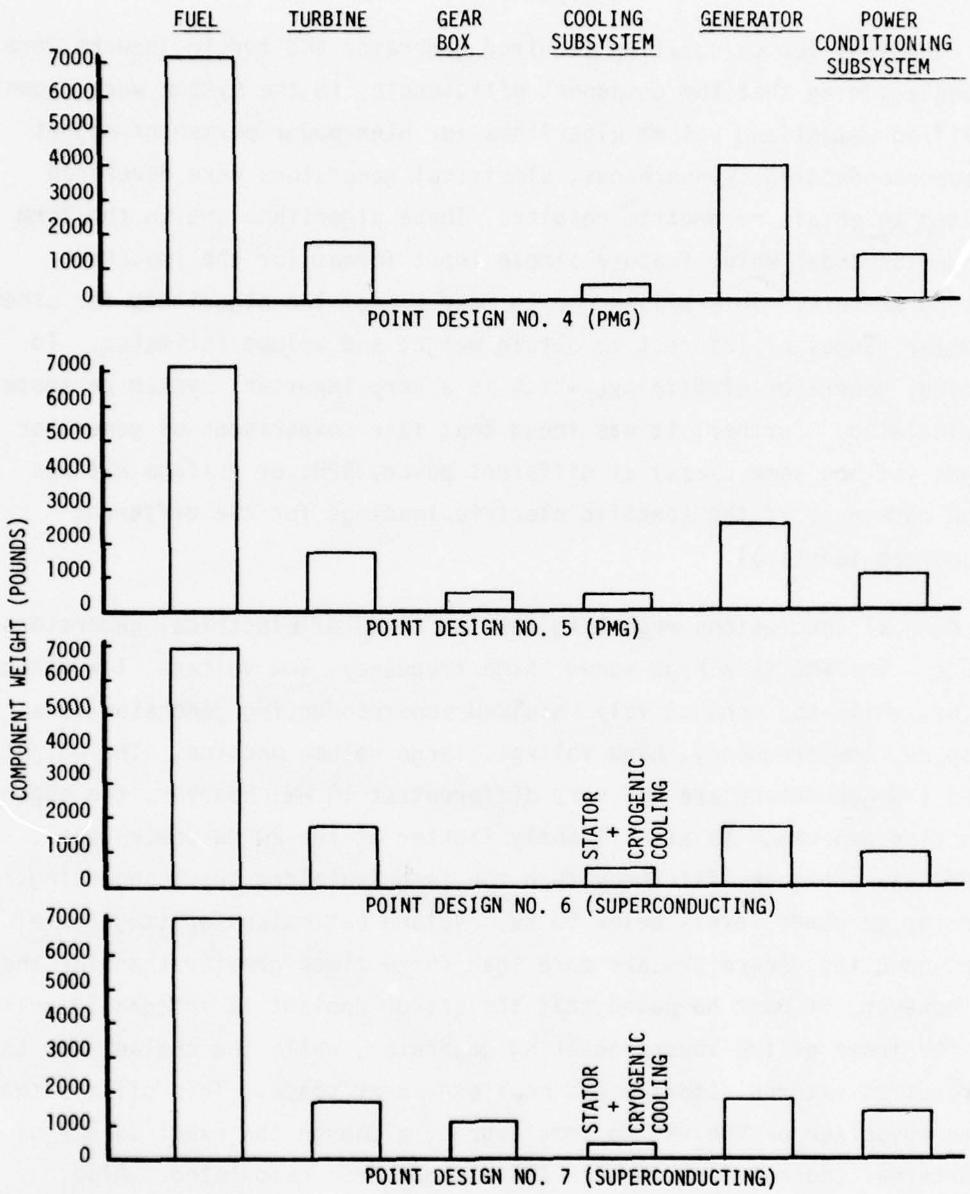


Figure 26. System Weight Distributions for the 20 MW Point Designs

SECTION VI

CONCLUSIONS

Equations for calculating required generator and turbine powers were derived assuming that the component efficiencies in the system were known. Simplified weight and volume algorithms for high power permanent magnet and superconducting, synchronous, electrical generators were developed and used to obtain parametric results. These algorithms are in the form of computer codes which feature simple input format for the important input parameters. This allows one to make use of the algorithms for other parameter ranges of interest to obtain weight and volume estimates. In addition, generator efficiency, which is a very important system parameter, is calculated. Further, it was found that fair comparisons of generator designs (of the same class) at different power, RPM, or voltage ratings can be made only if the specific electric loadings for the different designs are identical.

General conclusions regarding the two kinds of electrical generators include: The PMG is a high speed, high frequency, low voltage, low volume machine, while the conductively shielded superconducting generator is a low speed, low frequency, high voltage, large volume machine. The weights of the two generators are not very different at 10 MW; however, the superconducting generator is significantly lighter at the 20 MW power level. The PMG has a higher efficiency than the image-shielded superconducting generator at power levels below 50 MW. Volume estimates for image-shielded superconducting generators are more than three times greater than for the PMG; however, it must be noted that the stator coolant is integrally built into the frame of the superconducting generator, while the coolant for the PMG requires external storage and heat exchanger space. This offsets the volume advantage of the PMG to some degree, although the exact volume of the external coolant loop for the PMG has not been calculated. Also, image-shielded superconducting generators are inherently of large volume but very low weight. Superconducting generators using iron shields will have much smaller envelope volumes; however, the iron will tend to make these machines heavier than their image (conductively) shielded counterparts. Although these general conclusions are valid, a true comparison

of the two classes of electrical generators can only be made by comparing complete power supply systems as described below.

The generator algorithms plus the component algorithms in Appendix C were used to obtain system point designs at 10 and 20 MW power levels. From the system point designs, the two classes of electrical generators can be compared. From Figure 27, it can be seen that the PMG results in the lightest system at the lower power level, while the superconducting generator results in the lightest system at the higher power level. The two lightest systems are quite different, besides having different kinds of generators. The PMG is gear box driven and operates at a high electrical frequency, but the superconducting generator is directly driven from the turbine and operates at a lower electrical frequency. These differences account, in part, for the relatively small variance in system weight between the point designs at a given power level. For example, even though the superconducting generator is much lighter than the four PMG modules at the 20 MW power level, the low electrical frequency of the superconducting machine imposes a weight penalty in the power conditioning subsystem (transformer and filter). The weight differences between the lightest and second lightest systems are 440 and more than 1500 pounds for the 10 and 20 MW systems, respectively, and are significant from a mission payload/performance perspective. Although the individual component algorithms are only 10% accurate, a comparison of systems using the same algorithms should be valid. In other words, even with the most detailed point designs for every single component of the power supply system (rather than the approximate algorithms of this report), the relative weight standings shown in Figure 27 for the seven point designs should not change dramatically; however, the absolute magnitudes of the system weights would most likely shift upward.

The lower efficiency of the superconducting generator is offset to some degree by the absence of a high-power transformer and the attendant gain in system efficiency. This is illustrated by the fact that the fuel supply for both PMG and superconducting systems weigh about the same.

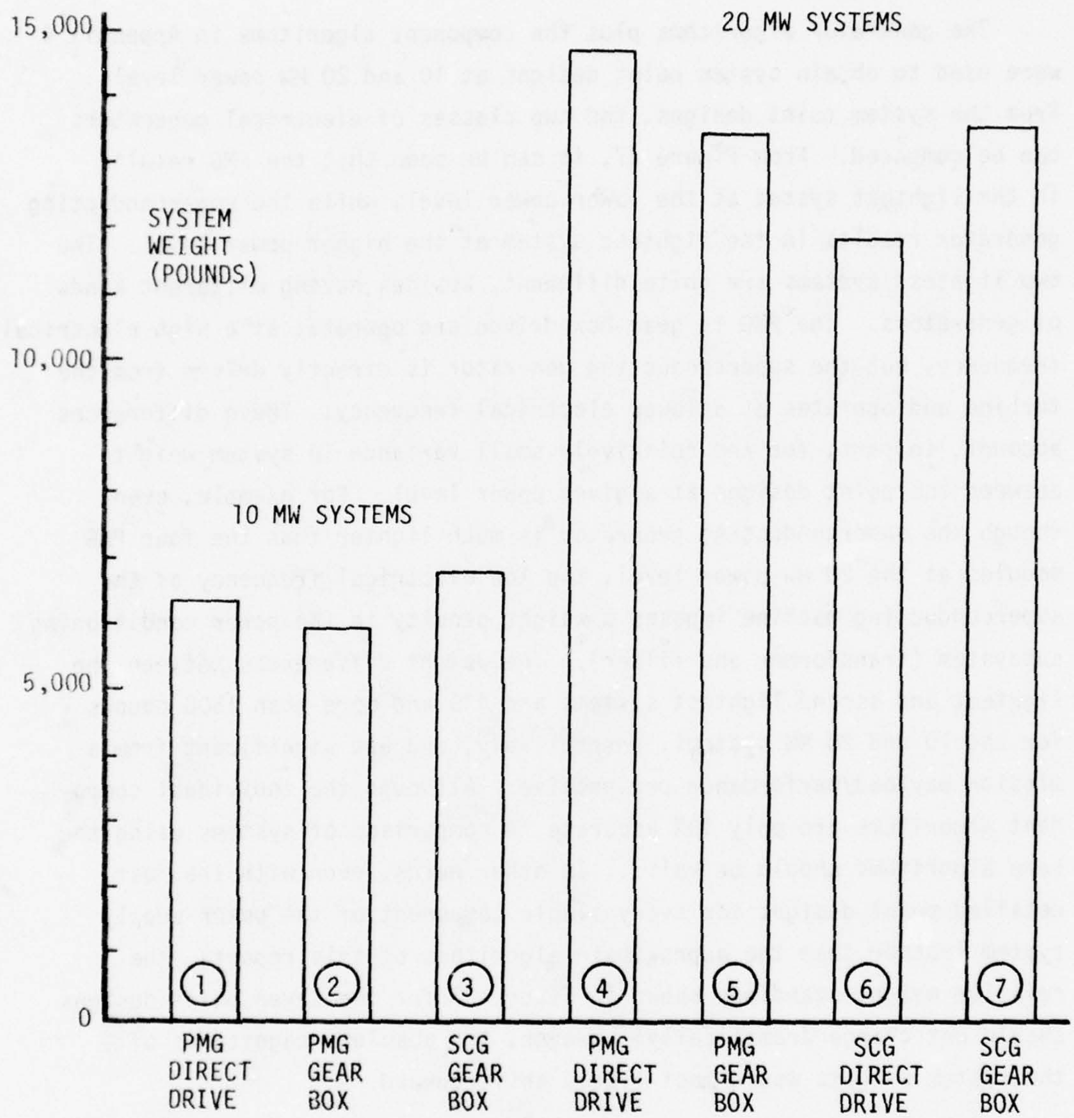


Figure 27. System Weights for the Seven Point Designs

This, and the fact that the weight of the fuel is a large part of the total system weight, are other reasons for the relatively small variance between the weights of the system point designs at similar power levels. However, again, the importance and significance of the weight differences must be emphasized. Also, the higher operating frequency of the PMG tends to make the power conditioning equipment lighter for this system; this is not apparent in Figures 26 and 27 because the PMG power conditioning subsystem includes a high-power transformer and the superconducting power conditioning subsystem does not.

There are certainly factors other than system weight which must be considered in selecting a generator. For example, in point design number 6, which is the lightest system at the 20 MW power level, the superconducting generator is directly driven by the turbine at 10,500 RPM. This will require careful design of the superconducting field coils, coil support structure, and helium management system for operation at this high speed. A 12,000 RPM superconducting rotor has already been built and tested by Westinghouse Electric Corporation (Reference 14).

It would obviously be desirable to improve the accuracy and/or flexibility of the two generator computer programs. One area for improvement would be to more accurately determine the weight and volume penalties associated with interconnecting the 5 MW PMG modules. Another would be to expand subroutine MFLD in the superconducting generator program to include other field winding configurations. In addition, it would be useful to consider the effect of reducing the "air gap" in the superconducting machine for higher rotational speeds as the rotor decreases in diameter. This could be done by reducing the thicknesses of the EM shield and/or the torque tube. Calculation of the machine inductances for different designs in order to determine voltage regulation and the effects of operating with rectified output or pulse forming subsystems is also needed.

From the overall system viewpoint, estimates of component volumes such as the turbine, fuel supply, cooling subsystems, and power conditioning components are required. One further step would be to consider

packaging and interconnection constraints in assembling the power supply system into the compact quarters of an aircraft.

Computer programs such as those described in this report are used as part of the AFAPL computer-aided power system design in-house research effort. These programs are used to predict the weight and size of components in high-power, airborne, power supply systems. These programs yield approximate weights and volumes, since they are not detailed design programs; the results should nevertheless be useful in feasibility and tradeoff studies concerning these two kinds of generators. One of the major advantages of this kind of "approximate" program is the fact that it adapts easily to "computerization" and allows a large number of point designs to be made with moderate computer time.

APPENDIX A

GENERATED VOLTAGE IN ALTERNATING-CURRENT SYNCHRONOUS MACHINES

Figure 28 illustrates the rotor of an AC, synchronous generator (alternator) with the projection of stator coil (aa') area shaded. All dimensions are assumed to be in meters and the angle θ is measured as indicated. The area of the projection is $\pi DL/p$ square meters for a p pole machine. It is assumed that the rotor produces a sine wave of magnetic flux density, which is shown in Figure 29 at a given time, t. The average flux density linking coil aa' at this time is given by

$$B_{avg}(t) = \frac{1}{\pi}\int_{-\omega t}^{\pi-\omega t} B \sin\theta \, d\theta = \frac{2B}{\pi} \cos\omega t, \text{ (webers/m}^2\text{)} \tag{76}$$

where θ is the angular displacement and B is the peak value of the sine wave of magnetic flux density. The average flux linking coil aa' at time t is just the area times the flux density, or

$$\phi_{avg}(t) = \phi_e \cos\omega t, \text{ (webers)} \tag{77}$$

where

$$\phi_e = 2DLB/p \quad \text{(webers)} \tag{78}$$

is the total "effective webers per pole" and can be written as

$$\phi_e = [\pi DL/p] \times [2B/\pi], \text{ (webers)} \tag{79}$$

where the first term is the area projected onto the rotor, and the second term is the average value of a positive half-cycle of a sine wave.

For a coil with N turns connected in series and linking the same flux, the generated voltage is given by (Reference 10)

$$E_g = - N \frac{d}{dt} \phi_{avg}(t) \text{ (volts)} \tag{80}$$

or

$$E_g = - N (d\phi_e/dt) \cos\omega t + \omega N\phi_e \sin\omega t \text{ (volts)} \tag{81}$$

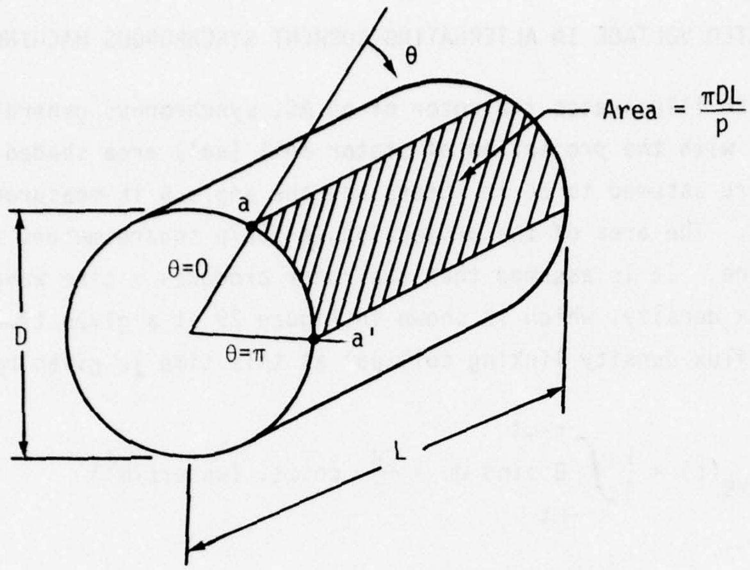


Figure 28. Projection of the Area Enclosed by a Stator Coil (aa') onto the Surface of the Rotor

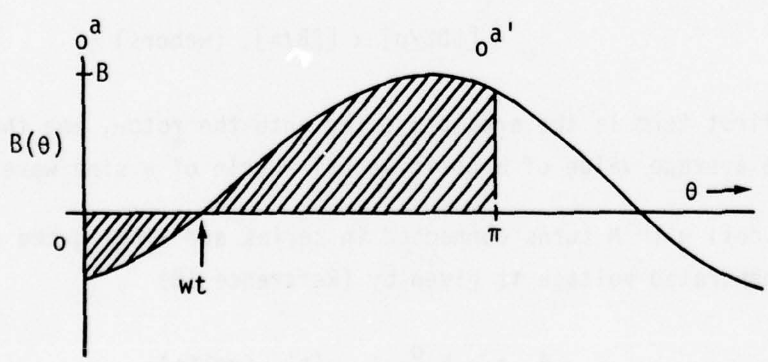


Figure 29. Magnetic Flux Density Variation in the Stator Winding (Coil aa')

If ϕ_e does not change with time (as is usually the case),

$$E_g = \omega N \phi_e \sin\omega t. \text{ (volts)} \tag{82}$$

The rms voltage per phase is just

$$V_{ph} = \omega N \phi_e / \sqrt{2}$$

$$V_{ph} = 4.44 \; f \; N\phi_e \text{ (volts rms)} \tag{83}$$

By including a winding factor, K_w, which accounts for the distribution of the stator coils relative to the spacing of the field poles, the generated phase voltage becomes

$$V_{ph} = 4.44 \; f \; K_w \; N \; [2DLB/p], \text{ (volts rms)} \tag{84}$$

where the expression for N is given below Equation 9 in the text. Converting from MKS to English units then yields Equation 9 in the text.

APPENDIX B

COMPUTER CODE LISTINGS AND SAMPLE OUTPUTS

The following computer code listings and sample outputs are given for reference. Sample outputs were obtained directly from the listings indicated. Fortran IV programming language was used throughout and comment cards were liberally employed which should make the programs easier to understand.

Input parameters appear at the beginning of each program and can be varied by changing the value of any input parameter at this point in the program.

All of the component mass densities for the PMG and superconducting generator are given in Tables 7 and 8 respectively.

Figure 30 is referenced in the superconducting generator program SCGEN.

TABLE 7

DENSITIES OF PMG COMPONENTS

COMPONENT	DENSITY (lbs/cu.in.)
Stator yoke	0.2815
Stator teeth	0.2815
Stator insulation	0.100
Rotor (overall)	0.238
Copper conductors	0.320

TABLE 8

DENSITIES OF SUPERCONDUCTING GENERATOR COMPONENTS

COMPONENT	DENSITY (lbs/cu.in.)
Environmental shield (components 1 and 2 in the computer program)	0.10
End bells	0.28
Field coils (epoxy-impregnated modules with a 75% copper packing factor)	0.75X 0.32+ 0.25X 0.10 = 0.265
Anti-drive end structure	0.28
Drive end structure	0.20
Torque tube	0.28
Bore tube	0.28
Field winding support structure	0.10
Electromagnetic shield (rotor shield)	0.10
Copper conductors	0.32
Stator insulation	0.10
Bore seal	0.10

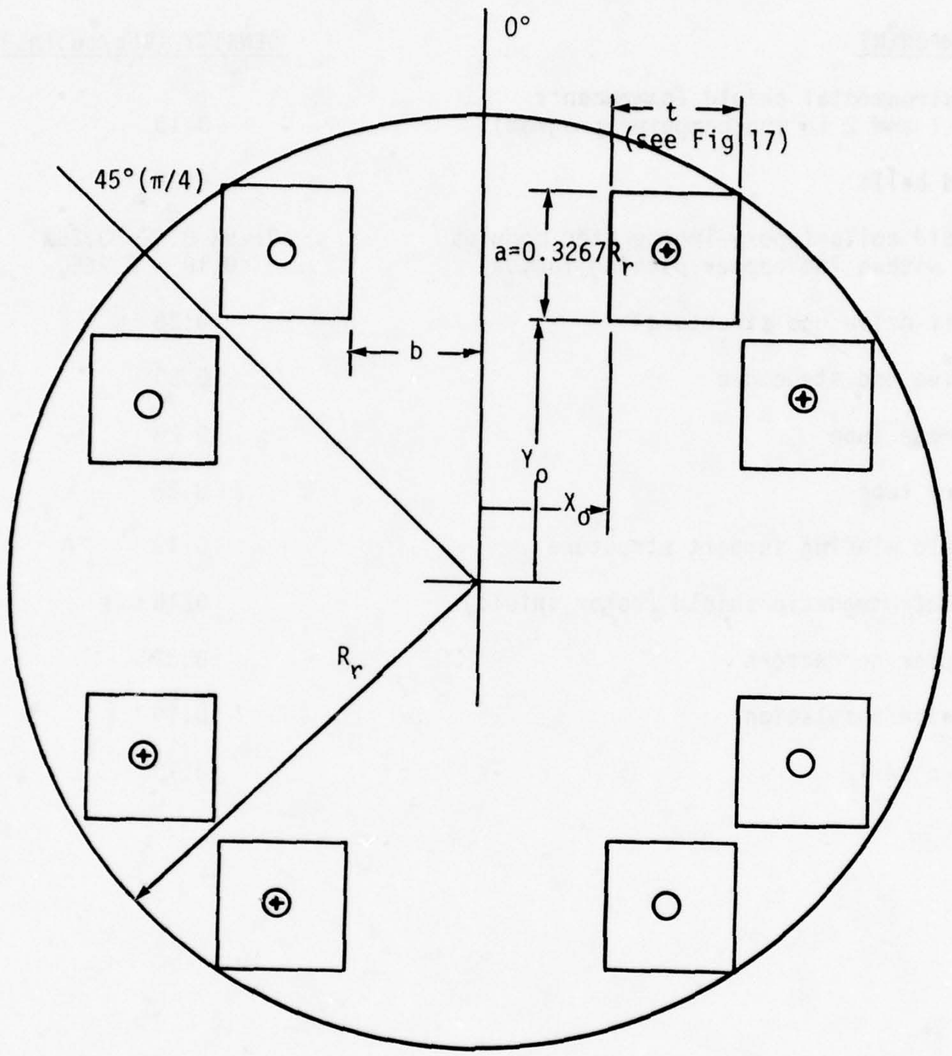


Figure 30. Four-Pole Rotor Geometry

PERMANENT MAGNET GENERATOR WEIGHT AND VOLUME COMPUTER PROGRAM

```
      PROGRAM PMG(OUTPUT)
      DIMENSION PP(500)
C THIS PROGRAM CALCULATES THE WEIGHT AND VOLUME OF PERMANENT MAGNET GENERATORS
C *********          *********          *********          *********          *********
C *** PERMANENT MAGNET GENERATOR  BASE LINE DESIGN  ***
C *****       *****       *****       *****       *****       *****       *****
C *****  THE FOLLOWING GENERATOR PARAMETERS MUST BE SPECIFIED FOR   ********
C ****    A GENERATOR POINT DESIGN
C     SPECIFY THE GENERATOR OUTPUT POWER IN WATTS
      PG=5.00E+05
C     GENERATOR RPM
      RPM=18000.
C     PHASE VOLTAGE (VOLTS RMS)
      VPH=588.0
C     LOAD POWER FACTOR
      PF=.82
C     COPPER CURRENT DENSITY IN THE STATOR (AMPS/SQ.IN.)
      CJ=36270.00
C     ROTOR TIP SPEED (FT/SEC)
      VT=625.50
C     NUMBER OF POLES
      P=14.0
C     NUMBER OF PHASES IN THE STATOR WINDING
      PH=3.
C *** DEFINE THE PITCH AS A FRACTION OF PI (OR 180 DEGREES ELECTRICAL)
      PI=3.1415927
      PITCH=(5.0/6.0)*PI
C *** SPECIFY THE STATOR INSULATION RATING IN VOLTS/MIL
      VPMIL=100.00
C     PEAK MAGNETIC FLUX DENSITY IN THE AIR GAP (LINES/SQ.IN.) UNDER LOAD
      BG=47400.0
C     SPACE FACTOR FOR STATOR BAR COOLING
      F=.85
C     RATIO OF FLUX DENSITY IN THE TOOTH TO THAT IN THE AIR GAP
      ALPH=2.20
C     RATIO OF SHAFT OD TO ROTOR OD
      FR=0.406
C     END TURN ANGLE
      CHI=PI/4.5
C *** SET THE ALLOWABLE FLUX DENSITY IN THE BACK-IRON (LINES/IN**2) ***********
      BYOKE=100000.0
C ****************      END OF POINT DESIGN SPECIFICATION   ****************
C *** MAXIMUM SPECIFIC ELECTRIC LOADING (AMPERE-CONDUCTORS/INCH)
      QMAX=4000.
C     RATIO OF FLUX DENSITY IN THE GAP TO THAT IN THE STATOR YOKE
      BGBY=BG/BYOKE
C *** CALCULATE THE PEAK FLUX DENSITY IN THE YOKE IN KLINES/IN**2 ***
      BYKL=BYOKE/1000.0
C *** CALCULATE THE PEAK FLUX DENSITY IN THE TEETH IN KLINES/IN**2 ***
      BTETH=BG*ALPH/1000.00
C ***********  SET THE COMPONENT MASS DENSITIES (IN LBS/ CUBIC INCH) **********
C     DENSITY OF STATOR YOKE
      RY=.2815
C     DENSITY OF STATOR TEETH
```

```
      RT=.2815
C     DENSITY OF INSULATION IN THE STATOR SLOTS
      RINS=.10
C     ROTOR DENSITY
      RR=.238
C     COPPER DENSITY
      RCU=.32
C *** BEGINNING OF GENERATOR DESIGN LOOP   **********
C     INITIALIZE THE NO. OF CONDUCTORS PER SLOT TO TWO
      CS=2.
C     ANS = NO. OF SLOTS PER POLE PER PHASE
      ANS=4.00
550   CONTINUE
C     CALCULATE THE OUTPUT POWER IN MEGAWATTS
      W=1.E-06*PG
C *** CALCULATE THE FREQUENCY (HERTZ)   **********
      FREQ=(P/2.0)*(RPM/60.00)
      PRINT 177,VPH,RPM,W,FREQ
C ****** CALCULATE THE ROTOR DIAMETER ********
      D=(720.*VT)/(PI*RPM)
C *** CALCULATE THE QUANTITY L PRIME USED IN THE COMPONENT VOLUME EXPRESSIONS
      ALP=(D/(1.414*SIN(CHI)))*SQRT(1.-COS(2.*PI/P))
C     CALCULATE THE THICKNESS OF THE STATOR YOKE(BACK IRON)
      DY=(D/P)*BGBY
C     CALCULATE THE RATED PHASE CURRENT(AMPS RMS)
      AMP=(PG/PF)/(PH*VPH)
C     D1=INSULATION THICKNESS FOR LINE TO NEUTRAL VOLTAGE (WALL INSULATION)
      D1=(SQRT(2.)*VPH/VPMIL)*1.E-03
C     D2=INSULATION THICKNESS BETWEEN COILS
      D2=D1*2.0
C     CALCULATE THE TOTAL NO. OF ACTIVE CONDUCTORS IN THE STATOR
  664 Z=ANS*P*PH*CS
C     CALCULATE THE TOTAL NO. OF SLOTS
      SLOTS=ANS*P*PH
C **********  CALCULATE THE POSSIBLE NUMBER OF PARALLEL PATHS  *************
C ********    IN THE STATOR WINDING     **************
      FIG=ANS*P
      DIV=1.0
      I=1
  453 DIVR=FIG/DIV
      PPT=IFIX(DIVR)
      PPT2=DIVR-PPT
      IF(PPT2.EQ.0.0) GO TO 450
      GO TO 455
  450 PP(I)=DIVR
      IM=I
      I=I+1
  455 DIV=DIV+1.0
      IF(DIV.GT.FIG) GO TO 452
      GO TO 453
  452 CONTINUE
      PRINT 458
  458 FORMAT(1H1,14HPARALLEL PATHS,/)
      DO 456 I=1,IM
  456 PRINT 457,I,PP(I)
  457 FORMAT(I10,F20.7)
C ********************  END PARALLEL PATH CALCULATION  **********************
C *** CALCULATE THE WINDING FACTOR AS THE PRODUCT OF THE PITCH FACTOR
```

```
C *** AND THE DISTRIBUTION FACTOR
C *** CALCULATE THE PITCH FACTOR
      AKP=SIN(PITCH/2.00)
C *** CALCULATE THE DISTRIBUTION FACTOR FROM THE NUMBER OF COILS IN
C *** EACH PHASE GROUP AND THE ELECTRICAL RADIANS BETWEEN SLOTS ( B )
      B=PITCH/(ANS*PH)
      AKD=(1.00/ANS)*(SIN((ANS*B)/2.00))/SIN(B/2.00)
C *** CALCULATE THE COMBINED WINDING FACTOR
      AKW=AKP*AKD
C *** ITERATE ON PPATH FOR GIVEN VALUES OF ANS AND CS  ********
      DO 668 I=1,I1
      PPATH=PP(I)
C *** CALCULATE THE CURRENT PER CONDUCTOR (AMPS RMS) ****
      AMPC=AMP/PPATH
C *** CALCULATE THE STACK LENGTH ***
C *** THE FACTOR (CS/2.000)**(-.06546) ACCOUNTS FOR SLOT LEAKAGE AS THE NO.
C *** OF CONDUCTORS PER SLOT INCREASES
      AL=VPH/(7.4018E-10*RPM*AKW*((P/PPATH)*ANS*(CS/2.))*D*BG*(CS/2.000)
     &**(-.06546))
C *** CALCULATE THE SPECIFIC ELECTRIC LOADING ***
      QL=(Z*AMPC)/(PI*(D+.50))
      IF(QL.GT.QMAX) GO TO 150
C     CHECK PHASE VOLTAGE(VPH1   SHOULD EQUAL VPH)
      VPH1=3.7009E-10*AKW*RPM*D*AL*BG*((CS/2.000)**(-.06546))*((Z/(PPATH
     &*PH)))
C     CHECK POWER (WC SHOULD EQUAL W)
      WC=AMP*PF*PH*VPH1
C     CALCULATE THE SLOT WIDTH(IN)
      S=(PI*D*(ALPH-1.))/(ALPH*SLOTS)
C     C=CONDUCTOR (BAR) WIDTH (INCHES)
      C=S-2.*D1
C     CHECK TO SEE IF THE CONDUCTOR WIDTH IS POSITIVE
      IF(C.LE.0.0) GO TO 250
C *** CALCULATE THE SLOT DEPTH ***
      DT=(CS*AMPC)/(F*C*CJ)+(CS-2.0)*.D1+D1+2.0*D2
C *** CALCULATE THE AREA OF A SINGLE CONDUCTOR IN SQUARE INCHES ***
      AC=AMPC/CJ
C     WEIGHT CALCULATIONS ( ELECTROMAGNETIC WEIGHT )
C     WY=BACK IRON (YOKE) WEIGHT (POUNDS)
      WY=RY*(PI*DY*(D+2.*DT+DY)*AL)
C     WT=WEIGHT OF THE TEETH (POUNDS)
      WT=RT*(PI*(D+DT)*DT*AL)/ALPH
C     WINS= INSULATION WEIGHT IN THE STATOR(POUNDS)
      WINS=RINS*(S*DT-(CS*AMPC)/CJ)*SLOTS*(AL+2.*ALP)
C     WR= ROTOR WEIGHT(POUNDS)
      WR=RR*((PI/4.)*(D**2)*(1.-FR**2))*AL
C     WCU=WEIGHT OF THE COPPER IN THE STATOR COILS(POUNDS)
      WCU=RCU*SLOTS*AC*CS*(AL+ALP)
C     WTOT=TOTAL ELECTROMAGNETIC WEIGHT (POUNDS)
      WTOT=WY+WT+WINS+WR+WCU
C     TOTAL MACHINE WEIGHT = WMACH(POUNDS)
      WMACH=1.200*WTOT
C     CALCULATE THE SPECIFIC WEIGHT IN LBS/KW
      SW=(WMACH/PG)*1000.00
C     CALCULATE THE FRAME RADIUS(IN)
      RFRM=(D+.50+2.*DT+2.*DY+2.00)/2.00
C     FRDIA=FRAME DIAMETER(IN)
      FRDIA=2.0*RFRM
```

```
C     CALCULATE THE TOTAL MACHINE VOLUME IN CUBIC FEET
      VOL=(PI*RFRM**2)*(AL+ALP*COS(CHI))/1728.00
C ** THE AVG. TEMPERATURE OF THE STATOR BARS IS ASSUMED TO BE TC DEGREES CENT.
      TC=232.0
C *** CALCULATE THE STATOR BAR RESISTIVITY IN OHM-INCHES ***
      RHOC=6.772E-07*(234.5+TC)/254.5
C *** CALCULATE THE OHMIC HEATING PER CUBIC INCH OF STATOR COPPER ***
      PIRV=CJ*CJ*RHOC
      PRLOS=PIRV*(WCU/RCU)
C *** CALCULATE THE HYSTERESIS LOSS IN THE YOKE ***
      PHY=7.1E-05*FREQ*BYKL**1.60
C *** CALCULATE THE EDDY CURRENT LOSSES IN THE YOKE ***
      PEY=4.3E-09*FREQ**2*BYKL**2
C *** CALCULATE THE HYSTERESIS LOSSES IN THE TEETH ***
      PHT=7.1E-05*FREQ*BTEETH**1.60
C *** CALCULATE THE EDDY CURRENT LOSSES IN THE TEETH ***
      PET=4.3E-09*FREQ**2*BTEETH**2
C *** CALCULATE THE LOSSES IN WATTS BY MULTIPLYING BY THE WEIGHTS IN POUNDS ***
      PYK=WY*(PHY+PEY)
      PTH=WT*(PHT+PET)
C *** CALCULATE THE TOTAL IRON LOSSES ***
      PIRON=PYK+PTH
C *** CALCULATE THE TOTAL STATOR LOSS (WATTS)
      PLOSS=PRLOS+PIRON
C *** CALCULATE THE MACHINE EFFICIENCY BASED ON STATOR LOSSES ONLY ***
      EFF=(PG/(PG+PLOSS))*100.00
      GO TO 665
  150 PRINT 151
      PRINT 166,PPATH,ANS,CS,QL
      GO TO 668
  250 PRINT 251
      PRINT 166,PPATH,ANS,CS,QL
      GO TO 668
  665 PRINT 30,SW,RPM,AMPC,VPH1,AMP,AKW
      PRINT 200,ANS,CS,PPATH,SLOTS,S,DT,DY
      PRINT 300,WY,WT,WINS,WR,WCU,WTOT,WMACH
      PRINT 400,Z,D,AL,VOL,QL
      PRINT 401, EFF,PLOSS,PRLOS,PYK,PTH
  668 CONTINUE
  950 CONTINUE
   30 FORMAT(//,3X*SPEC. WEIGHT*3X*RPM*9X*AMPC*8X*CALCULATED PHASE VOLTA
     $GE*2X*CURRENT(AMPS)*2X*WINDNG PTCH+DIST FACTOR*/3F12.3,F24.6,2F20.
     $6/)
  200 FORMAT(*  NO.SL/P/PH     CS        PPATHS          NUMBER OF SLOTS  SL
     $OT WIDTH      SLOT DEPTH      YOKE DEPTH*/3F10.3,5X,4F15.3/)
  300 FORMAT(5X*WEIGHTS-LBS.*4X*YOKE*10X*TEETH*8X*INSULATION*7X*ROTOR*9X
     $*COPPER*9X*TOTAL*9X*MACHINE*/10X,7F15.2/)
  400 FORMAT(3X*TOTAL NO. COND.    ROTOR DIA(IN)    STATOR LEN(IN)    VOLUME
     $*6X*SPEC.LOAD*/5F15.4/)
  401 FORMAT(/,5X,13HEFFICIENCY = ,F7.2,3X,7HLOSS = ,F8.1,3X,8HOHMIC = ,
     $F8.1,3X,7HYOKE = ,F8.1,3X,8HTEETH = ,F8.1,/)
  151 FORMAT(16H LOADING EXCEDED)
  251 FORMAT(19H NO ROOM FOR COPPER)
  166 FORMAT(4F15.4,/)
  177 FORMAT(1H1,5H VPH=,F8.2,2X,4HRPM=,F10.2,2X,6HPOWER=,F12.2,2X,5HFRE
     $Q=,F12.2)
  900 STOP
      END
```

```
VPH=  588.00  RPM=  18000.00  POWER=         5.00  FREQ=      2100.00


PARALLEL PATHS

        1          56.0000000
        2          28.0000000
        3          14.0000000
        4           8.0000000
        5           7.0000000
        6           4.0000000
        7           2.0000000
        8           1.0000000

  SPEC. WEIGHT   RPM          AMPC         CALCULATED PHASE VOLTAGE  CURRENT(AMPS)  WINDNG PTCH+DIST FACTOR
     .375  18000.000        51.726                588.000000            3456.667220             .937424

 NO.SL/P/PH     CS        PPATHS          NUMBER OF SLOTS  SLOT WIDTH      SLOT DEPTH       YOKE DEPTH
   4.000      2.000     56.000                168.000             .081             .104            .270

   WEIGHTS-LBS.     YOKE             TEETH          INSULATION          ROTOR           COPPER            TOTAL             MACHINE
                  251.03             41.89            10.96            1234.99            23.33           1562.09            1874.51

  TOTAL NO. COND.   ROTOR DIA(IN)  STATOR LEN(IN)    VOLUME        SPEC.LOAD
    336.0000          7.9641         124.7141          7.2445        779.9692

   EFFICIENCY =   95.33   LOSS = 245171.7   OHMIC = 119028.3   YOKE = 106921.5   TEETH =  19221.9

  SPEC. WEIGHT   RPM          AMPC         CALCULATED PHASE VOLTAGE  CURRENT(AMPS)  WINDNG PTCH+DIST FACTOR
     .194  18000.000       123.452                588.000000            3456.667220             .937424

 NO.SL/P/PH     CS        PPATHS          NUMBER OF SLOTS  SLOT WIDTH      SLOT DEPTH       YOKE DEPTH
   4.000      2.000     28.000                168.000             .081             .166            .270

   WEIGHTS-LBS.     YOKE             TEETH          INSULATION          ROTOR           COPPER            TOTAL             MACHINE
                  127.36             33.74             7.57             617.45            23.83            809.94             971.93

  TOTAL NO. COND.   ROTOR DIA(IN)  STATOR LEN(IN)    VOLUME        SPEC.LOAD
    336.0000          7.9641          62.3570          3.7645       1559.9385

   EFFICIENCY =   96.31   LOSS = 191330.4   OHMIC = 121603.1   YOKE =  54245.9   TEETH =  15481.3

  SPEC. WEIGHT   RPM          AMPC         CALCULATED PHASE VOLTAGE  CURRENT(AMPS)  WINDNG PTCH+DIST FACTOR
     .104  18000.000       246.905                588.000080            3456.667220             .937424

 NO.SL/P/PH     CS        PPATHS          NUMBER OF SLOTS  SLOT WIDTH      SLOT DEPTH       YOKE DEPTH
   4.000      2.000     14.000                168.000             .081             .290            .2[illegible]

   WEIGHTS-LBS.     YOKE             TEETH          INSULATION          ROTOR           COPPER            TOTAL             MACHINE
                   65.52             29.95             6.11             308.72            24.84            435.14             522.16

  TOTAL NO. COND.   ROTOR DIA(IN)  STATOR LEN(IN)    VOLUME        SPEC.LOAD
    336.0000          7.9641          31.1785          2.0299       3119.8770

   EFFICIENCY =   96.74   LOSS = 168404.5   OHMIC = 126752.7   YOKE =  27908.1   TEETH =  13743.7
LOADING EXCEDED
        8.0000          4.0000          2.0000      5459.7847

LOADING EXCEDED
        7.0000          4.0000          2.0000      6239.7539

LOADING EXCEDED
        4.0000          4.0000          2.0000     10919.5694

LOADING EXCEDED
        2.0000          4.0000          2.0000     21839.1338

LOADING EXCEDED
        1.0000          4.0000          2.0000     43678.2776
```


SAMPLE OUTPUT — BASE-LINE DESIGN

SUPERCONDUCTING GENERATOR WEIGHT AND VOLUME COMPUTER PROGRAM

```
      PROGRAM SCGEN(OUTPUT)
      DOUBLE PRECISION PMU,RM1,RM2,RSM,DX,DY,X0,Y0,AI
      DOUBLE PRECISION BR1,BF1,BR2,BF2,BRM,BFM,BR,BTM,BRR,BFF,BT
      DIMENSION VOL(13),P(13)
      REAL KW,JC,MUE,L,LL,LC,IPHASE,LPRIME,LSM
C ********          ********          ********          ********          ********
C *** SUPERCONDUCTING GENERATOR  BASE LINE DESIGN  *******
C ********          ********          ********          ********          ********
C ***
C **********    THE FOLLOWING PARAMETERS MUST BE SPECIFIED          *************
C **********    FOR A GENERATOR POINT DESIGN                        *************
C *** SPECIFY THE GENERATOR OUTPUT POWER IN WATTS
      POWER =20.0E+06
C *** SPECIFY THE GENERATOR RECTIFIED OUTPUT VOLTAGE IN VOLTS
      VDC=40000.
C *** SPECIFY THE ROTATIONAL SPEED
      RPM=6000.
C *** SPECIFY THE NUMBER OF SLOTS PER POLE PER PHASE
      ANS=28.
C *** SPECIFY THE NUMBER OF CONDUCTORS PER SLOT
      CS=6.00
C *** SPECIFY THE EQUIVALENT POWER FACTOR
      PF=.860
C *** SPECIFY THE NUMBER OF PHASES
      PHASE=3.00
C *** SPECIFY THE STATOR CONDUCTOR CURRENT DENSITY IN AMPS/SQ.IN. ***
      JC=29400.00
C *** SPECIFY THE SUPERCONDUCTING FIELD WINDING COIL MODULE OVERALL
C *** CURRENT DENSITY IN AMPS/CM**2
      ACM=15000.00
C *** SPECIFY THE TIP SPEED OF THE FIELD COILS IN FEET/SEC  ***
      VT=471.0
C *** SPECIFY THE DISTANCE FROM THE OUTER RADIUS OF THE STATOR WINDING TO
C *** THE INNER RADIUS OF THE ENVIRONMENTAL SHIELD IN INCHES
      S=7.0
C *** SPECIFY THE SUPERCONDUCTOR MINIMUM BEND RADIUS ***
      B=1.500
C ****************************************************************************
C *** NOTE THAT THE PROGRAM PRESENTLY CALCULATES THE HEIGHT (A) OF A FIELD COIL
C *** MODULE AS A FIXED FRACTION OF THE RADIUS OF THE ROTOR. THAT IS, A=.3267*RR
C *** THIS CAN BE MODIFIED TO ALLOW SPECIFICATION OF ANY FIELD COIL MODULE
C *** HEIGHT BY SIMPLY DELETING THIS CARD IN THE PROGRAM AND DEFINING A AT THIS
C *** POINT IN THE PROGRAM. FOR EXAMPLE, IF A WERE TO BE 2.30 INCHES, PLACE A
C *** CARD WITH  A=2.30  AT THIS POINT IN THE PROGRAM.
C ****************************************************************************
C *** SPECIFY THE ARMATURE WINDING DISTRIBUTION FACTOR
      KW=1.00
C *** SPECIFY THE STATOR BAR PACKING FACTOR ( I.E., THE RATIO OF COPPER TO
C *** INSULATION IN A SINGLE RECTANGULAR SLOT
      FBAR=.450
C *** SPECIFY THE DISTANCE FROM THE EM SHIELD OUTER RADIUS TO THE BORE SEAL
C *** INNER RADIUS IN INCHES.  THIS IS THE PHYSICAL AIR GAP
      G=.200
C *** SPECIFY THE STATOR BAR END TURN ANGLE IN RADIANS
      X=.698
C *** HO IS THE HEIGHT AND WIDTH OF A SQUARE , HOLLOW CONDUCTOR WITH A WALL
C *** THICKNESS OF TW METERS. HO IS ALSO IN METERS.
```

```
      HO=3.55E-03
      TW=8.255E-04
      TI=HO-2.*TW
C **********     END OF POINT DESIGN SPECIFICATION    **********************
C ***
C *****  THE NUMBER OF POLES IS LIMITED TO FOUR FOR THIS PROGRAM   *******
      POLES=4.00
C *** DELTAB=THE BORE TUBE THICKNESS IN INCHES
      DELTAB=.50
C *** DELTAT=THE TORQUE TUBE THICKNESS IN INCHES
      DELTAT=0.500
C *** DELTAS=THE ELECTROMAGNETIC SHIELD THICKNESS IN INCHES
      DELTAS=.75
C *** DELTAE=THE ENDBELL THICKNESS IN INCHES
      DELTAE=.50
      PI=3.1415927
      ANG=PI/POLES
C *** U0 IS THE PERMEABILITY OF A VACUUM
      U0=1.256637E-06
C *** SIGMA IS THE CONDUCTIVITY OF ALUMINUM IN MHOS/METER
      SIGMA=3.77E+07
  833 CONTINUE
C *** CALCULATE THE FIELD WINDING OD ***
      DR=(720.*VT)/(PI*RPM)
C *** RR IS THE RADIUS OF THE FIELD WINDING STRUCTURE IN INCHES
      RR=DR/2.
C *** CALCULATE THE BORE SEAL THICKNESS IN INCHES   ************
      VDCK=VDC/1000.0
      AK=1.732
      EI=4.10
      EO=2.10
C *** DBSEL IS THE BORE SEAL THICKNESS IN INCHES
      DBSEL=(1.083E-04*(EI/EO)*(AK*VDCK)**1.68)
C *** DBAR IS THE INSULATION THICKNESS BETWEEN STATOR BARS OF THE SAME PHASE
C *** IN INCHES
      DBAR=.0200
C *** DPH IS THE INSULATION THICKNESS BETWEEN STATOR BARS OF DIFFERENT
C *** PHASE VOLTAGES IN INCHES
      DPH=.500
C *** DCON IS THE STATOR CONDUCTOR INSULATION THICKNESS IN INCHES.
      DCON=.005
C *** CALCULATE THE GENERATOR LINE-TO-NEUTRAL VOLTAGE IN VOLTS
      VPHASE=VDC/2.3
C *** CALCULATE THE HEIGHT OF A WINDING MODULE ***
C *** SEE NOTE UNDER GENERATOR INPUT PARAMETER DEFINITION
      A=0.3257*RR
C *** CALCULATE THE WIDTH OF A FIELD WINDING MODULE ***
      T=.9*(RR-A*COS(ANG))*SIN(ANG)-B
C *** CALCULATE THE AREA OF A MODULE IN CM**2
      ARCM=A*T*2.54*2.54
C *** CALCULATE THE TOTAL CURRENT PER MODULE SIDE
      CURR=ACM*ARCM
C *** CALCULATE THE CURRENT PER WIRE BASED ON 144 WIRES
      AI=CURR/144.00
      RM=RR*.0254
      AM=A*.0254
      TM=T*.0254
```

```
      CH=SQRT(RM**2-(.0254*B+TM)**2)
      DX=(T/12.)*.0254
      DY=(A/12.)*.0254
      X0=.0254*B+DX/2.0
      Y0=CH-AM+DY/2.0
C *** CALCULATE THE ID OF THE STATOR ***
      D=2.*(RR+DELTAT+DELTAS+G)
      R=D/2.00
C *** CALCULATE THE TOTAL NUMBER OF SLOTS IN THE STATOR
      SLOTS=ANS*PHASE*POLES
C *** CALCULATE THE SLOT WIDTH IN INCHES
      SWIDTH=(PI*D-PHASE*POLES*DPH-(ANS-1.0)*PHASE*POLES*DBAR)/SLOTS
C *** CALCULATE THE PHASE CURRENT IN AMPERES(RMS)
      IPHASE=POWER/(PF*PHASE*VPHASE)
C *** CALCULATE THE AREA OF A SINGLE STATOR CONDUCTOR IN SQUARE INCHES
      AC=IPHASE/JC
      SCHK=SWIDTH-2.0*DCON
      IF(SCHK.LE.0.0) GO TO 150
C *** DA IS EQUAL TO THE THICKNESS OF THE BORE SEAL PLUS THE THICKNESS ****
C *** OF THE STATOR WINDING ***
      DA=(CS*IPHASE)/(SCHK*FBAR*JC)+(CS-1.0)*.01+2.0*DCON+DBSEL
C *** DARM IS THE THICKNESS OF THE ARMATURE ***
      DARM=DA-DBSEL
      FARM=(CS*AC*SLOTS)/(PI*D*DARM)
C *** CALCULATE THE SPECIFIC ELECTRIC LOADING (AMP-CONDUCTORS/INCH)
      Q=DARM*FARM*JC
C *** RS IS THE INSIDE RADIUS OF THE ENVIRONMENTAL IMAGE SHIELD ***
      RS=RR+DELTAT+DELTAS+G+DA+S
C *** CALCULATE THE INSIDE RADIUS OF THE STATOR WINDING
      RHO1=RR+DELTAT+DELTAS+G+DBSEL
C *** CALCULATE THE OUTER RADIUS OF THE STATOR WINDING
      RHO2=RHO1+DA-DCON-DBSEL
C *** CONVERT THE STATOR WINDING INNER RADIUS TO METERS
      RM1=.0254*RHO1
C *** CONVERT THE STATOR WINDING OUTER RADIUS TO METERS
      RM2=.0254*RHO2
C *** PMU IS THE ANGLE FROM THE COIL BORE  ( SEE FIGURE 30  IN THIS APPENDIX )
      PMU=0.0
C *** CALCULATE THE RADIAL(BR1) AND AZIMUTHAL(BF1) MAGNETIC FLUX DENSITIES AT
C *** THE INNER RADIUS OF THE STATOR WINDING
      CALL MFLD(RM1,PMU,BR1,BF1,X0,Y0,DX,DY,AI)
C *** CALCULATE THE RADIAL(BR1) AND AZIMUTHAL(BF1) MAGNETIC FLUX DENSITIES AT
C *** THE OUTER RADIUS OF THE STATOR WINDING
      CALL MFLD(RM2,PMU,BR2,BF2,X0,Y0,DX,DY,AI)
      PRINT 567, BF1,BF2
  567 FORMAT(//,2F20.5,//)
      BRP1=BR1
      BRP2=BR2
C *** CALCULATE THE AVERAGE OF THE TWO RADIAL FLUX DENSITIES AND CONVERT
C *** TO KILOGAUSS
      BKG=ABS(((BRP1+BRP2)/2.0)*10.0)
C *** CALCULATE THE ELECTRICAL FREQUENCY IN HERTZ
      FRE=(POLES/2.)*(RPM/60.)
C *** CALCULATE THE ELECTRICAL FREQUENCY IN RADIANS PER SECOND
      WF=2.0*PI*FRE
C *** CALCULATE THREE TIMES THE SKIN DEPTH OF THE ENVIRONMENTAL SHIELD IN IN.
      DELTA=3.0*SQRT(2.0/(WF*U0*SIGMA))/.0254
```

```
C *** CALCULATE THE TOTAL NUMBER OF ACTIVE CONDUCTORS IN THE STATOR
      Z=(PI*D*Q)/IPHASE
C *** CALCULATE THE EFFECTIVE ACTIVE STRAIGHT LENGTH OF THE STATOR
      L=POWER/(7.5E-06*PF*KW*RPM*D*D*BKG*Q)
C *** CALCULATE THE ACTUAL PHYSICAL STRAIGHT LENGTH WHICH IS SMALLER THAN L DUE
C *** TO THE EMF GENERATED IN THE END TURN REGIONS OF THE AIR GAP STATOR WINDING
      LL=L/1.233
C *** CALCULATE THE TOTAL LENGTH OF A RACETRACK FIELD COIL IN INCHES
      LC=LL+2.*(B+T)
C *** CALCULATE THE BORE TUBE INNER RADIUS IN INCHES
      RB=(RR-A*COS(ANG))/2.0
C *** CALCULATE THE BORE TUBE OUTER RADIUS IN INCHES
      RRS=RB+DELTAB
C *** V IS THE OUTER RADIUS OF THE STATOR WINDING
      V=RS-S
C *** RES IS THE OUTER RADIUS OF THE TORQUE TUBE
      RES=RR+DELTAT
C *** RESO IS THE OUTER RADIUS OF THE ELECTROMAGNETIC SHIELD
      RESO=RES+DELTAS
C *** RI IS THE INNER RADIUS OF THE BORE SEAL
      RI=RESO+G
C *** RO IS THE OUTER RADIUS OF THE STATOR WINDING (ALSO EQUAL TO V)
      RO=RESO+G+DA
C *** CALCULATE THE WIDTH OF A STATOR COIL IN INCHES
      W=(D/1.414)*SQRT(1.-COS(2.*ANG))
C *** E IS THE DISTANCE WHICH THE END TURN OF A STATOR COIL EXTENDS BEYOND
C *** THE STRAIGHT SECTION
      E=W/(2*TAN(X))
C *** CALCULATE THE TOTAL OVERALL LENGTH OF A STATOR COIL
      LPRIME=LL+2.*E
C *** CALCULATE THE COMPONENT VOLUMES IN CUBIC INCHES   **********
C *** VOL(1) IS THE VOLUME OF THE STRAIGHT CYLINDRICAL PORTION OF THE
C     ENVIRONMENTAL SHIELD
      VOL(1)=PI*LPRIME*(2.*DELTA*RS+DELTA**2)
C *** VOL(2) IS THE SUM OF THE VOLUME OF THE TWO CONICAL PORTIONS OF THE
C     ENVIRONMENTAL SHIELD
      VOL(2)=2.*PI*S*DELTA*(2.*RS+DELTA-S)
C *** VOL(3) IS THE VOLUME OF THE TWO END BELLS
      VOL(3)=2.*PI*(V**2-RRS**2)*DELTAE
C *** VOL(4) IS THE VOLUME OF THE FOUR FIELD COILS
      VOL(4)=(2.*LL*A*T+PI*A*(2.*B*T+T**2))*POLES
C *** VOL(5) IS THE VOLUME OF THE ANTI-DRIVE END STRUCTURE
      VOL(5)=PI*RRS**2*(LC/5.)
C *** VOL(6) IS THE VOLUME OF THE DRIVE END STRUCTURE
      VOL(6)=PI*RRS**2*(LC/5)
C *** VOL(7) IS THE VOLUME OF THE TORQUE TUBE
      VOL(7)=PI*(2.*DELTAT*RR+DELTAT**2)*(LC+S)
C *** VOL(8) IS THE VOLUME OF THE BORE TUBE
      VOL(8)=PI*LC*(2.*DELTAB*RB+DELTAB**2)
C *** VOL(9) IS THE VOLUME OF THE FIELD WINDING SUPPORT STRUCTURE
      VOL(9)=(PI*LC*(RR**2-RRS**2))-VOL(4)
C *** VOL(10) IS THE VOLUME OF THE ELECTROMAGNETIC SHIELD
      VOL(10)=(PI*LC)*(RESO**2-RES**2)+(PI*DELTAS)*(RESO**2-RRS**2)
C *** VOL(11) IS THE VOLUME OF THE COPPER STATOR CONDUCTORS
      VOL(11)=(Z*AC)*(LL+W/SIN(X))
C *** VOL(12) IS THE VOLUME OF THE STATOR INSULATION
      VOL(12)=(PI*LPRIME)*(RO**2-RI**2)-VOL(11)
```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SIGNIFICANT NUMBER OF PAGES WHICH DO NOT
REPRODUCE LEGIBLY.

```
C *** VOL(13) IS THE VOLUME OF THE BORE SEAL
      VOL(13)=PI*LPRIME*(2.*DBSEL*R+DBSEL**2)
C *** DEFINE THE COMPONENT MASS DENSITIES IN POUNDS PER CUBIC INCH ***
      P(1)=.1
      P(2)=.1
      P(3)=.28
      P(4)=.265
      P(5)=.28
      P(6)=.2
      P(7)=.28
      P(8)=.28
      P(9)=.1
      P(10)=.1
      P(11)=.32
      P(12)=.1
      P(13)=.10
      WT=0.0
C *** CALCULATE THE WEIGHT OF THE ROTOR IN POUNDS
      ROTWT=0.0
      DO 48 J=4,10
   48 ROTWT=ROTWT+P(J)*VOL(J)
C *** CALCULATE THE TOTAL ENVELOPE VOLUME OF THE SUPERCONDUCTING GENERATOR *****
C *** THE UNITS ARE IN CUBIC FEET  *******
      VOLUME=( LPRIME*PI*(RS+DELTA)**2 + 2.*S*PI*( 2.*RS**2+S**2-2.*S*RS
     &+RS*(RS-S) ) )/1728.0
C *** CALCULATE THE TRANSPORT CURRENT LOSSES (OHMIC HEATING) IN KILOWATTS ***
C *** CONVERT THE COPPER VOLUME IN CUBIC INCHES INTO CUBIC METERS
      VOLCU=VOL(11)*1.6387E-05
C *** CONVERT THE CONDUCTOR CURRENT DENSITY IN AMPS/SQ.IN. INTO AMPS/SQ.METER
      AJC=JC*1.55E+03
C *** CALCULATE THE RESISTIVITY OF COPPER(RHO IN OHM-METERS) AT TMPC DEGREES C *
      TMPC=150.0
      RHO=1.72E-08*(234.5+TMPC)/254.5
C *** PIRL IS THE TOTAL I SQUARED R LOSS IN KILOWATTS
      PIRL=AJC*AJC*RHO*VOLCU/1000.00
C *** CALCULATE THE EDDY CURRENT LOSSES IN THE STATOR BARS IN KILOWATTS ***
C *** CALCULATE THE PEAK TANGENTIAL MAGNETIC FLUX DENSITY AT BOTH THE INNER
C     AND OUTER RADII OF THE STATOR WINDING AT AN ANGLE PI/4 (IE HALF WAY
C     BETWEEN POLES) FROM THE COIL BORE (SEE FIGURE 30  IN THIS APPENDIX)
      PMU=0.250
      CALL MFLD(RM1,PMU,BR,BTM,X0,Y0,DX,DY,AI)
      CALL MFLD(RM2,PMU,BRR,BFF,X0,Y0,DX,DY,AI)
C *** CALCULATE THE AVERAGE OF THE TWO PEAK VALUES OF RADIAL MAGNETIC FLUX
C *** DENSITY AT THE INNER AND OUTER STATOR WINDING RADII
      BRPM=(BR1+BR2)/2.0
C *** CALCULATE THE AVERAGE OF THE TWO PEAK VALUES OF AZIMUTHAL MAGNETIC FLUX
C *** DENSITY AT THE INNER AND OUTER STATOR WINDING RADII
      BTPM=(BTM+BFF)/2.0
C *** CALCULATE THE EDDY CURRENT LOSSES IN WATTS/CUBIC METER
      PEV=(WF**2/(24.*RHO))*((H0**4-TI**4)/(H0**2-TI**2))*(BTPM**2+BRPM*
     &*2)
C *** REDUCE THE EFFECTIVE VOLUME OF STATOR COPPER TO ACCOUNT FOR THE FACT THAT
C *** MOST OF THE EDDY CURRENT LOSSES OCCUR IN THE STRAIGHT SECTION OF THE
C *** STATOR WINDING
      VOLCE=VOLCU*LL/(LL+W/SIN(X))
C *** CALCULATE THE TOTAL EDDY CURRENT LOSS IN KILOWATTS
      PEDD=PEV*VOLCE/1000.00
```

```
C *** CALCULATE THE LOSSES(EDDY CURRENT) IN THE IMAGE SHIELD IN KILOWATTS ***
C *** DEL IS THE SKIN DEPTH IN THE ALUMINUM ENVIRONMENTAL SHIELD
      DEL=SQRT(2./(WF*U0*SIGMA))
C *** RSM IS THE RADIUS OF THE ENVIRONMENTAL SHIELD IN METERS
      RSM=RS*.0254
C *** LSM IS THE LENGTH OF THE CYLINDRICAL PORTION OF THE ENVIRONMENTAL SHIELD
C *** IN METERS
      LSM=LPRIME*.0254
C *** CALCULATE THE PEAK VALUE OF THE AZIMUTHAL COMPONENT OF MAGNETIC FLUX
C *** DENSITY AT RADIUS RSM. NOTE THAT THE PEAK OF AZIMUTHAL FLUX DENSITY
C *** OCCURS MID WAY BETWEEN POLE CENTERS, THAT IS, AT AN ANGLE OF PI/4 FROM
C *** THE COIL BORE ( SEE FIGURE 30   IN THIS APPENDIX )
      PMU=0.250
      CALL MFLD(RSM,PMU,BR,BT,X0,Y0,DX,DY,AI)
C *** PSHLD IS THE EDDY CURRENT LOSS IN THE ENVIRONMENTAL SHIELD IN KILOWATTS
      PSHLD=(PI*RSM*LSM*BT*BT)/(SIGMA*DEL*U0*U0*1000.00)
C *** CALCULATE THE GENERATOR EFFICIENCY (PERCENT)
      EFF=(POWER/(POWER+1000.0*(PIRL+PEDD+PSHLD)))*100.00
C *** CONVERT THE CONDUCTOR HEIGHT FROM METERS TO INCHES
      HOI=H0*100.0/2.54
C *** CONVERT THE CONDUCTOR WALL THICKNESS FROM METERS TO INCHES
      TWI=TW*100.0/2.54
C *** CALCULATE THE POWER IN MEGAWATTS
      PM=POWER*1.E-06
C *** CONVERT THE END TURN EXTENSION ANGLE FROM RADIANS TO DEGREES
      XAN=(X/PI)*180.0
      PRINT 60
      PRINT 70, PM,VOC,RPM,FRE,JC,VT,PF,FBAR,KW
      PRINT 81
      PRINT 71,CS,ANS,Z,IPHASE,SLOTS,SWIDTH,DBAR,DCON,DPH
      PRINT 82
      PRINT 72, DELTAB,DELTAT,DELTAS,DELTAE,S,G,B,A,XAN
      PRINT 83
      PRINT 73, RR,D,RS,LL,LC,LPRIME,E,DBSEL,T
      PRINT 84
      PRINT 77, DA,DARM,HOI,TWI,W,DELTA,FARM,AC
      PRINT 85
      PRINT 74, BR1,BR2,BKG,BRM,BTM,BFF.BRPM,BTPM,BT
      DO 50 K=1,13
      WTC=P(K)*VOL(K)
      PRINT 65, K,WTC
   50 WT=WT+WTC
C *** CALCULATE THE SPECIFIC WEIGHT IN POUNDS PER KILOWATT
      SWT=1000.*WT/POWER
      PRINT 86
      PRINT 75, SWT,WT,ROTWT,VOLUME,Q,ACM
      PRINT 87
      PRINT 76, EFF,PIRL,PEDD,PSHLD
  331 GO TO 153
  150 PRINT 151
  153 CONTINUE
   65 FORMAT(I10,F12.2)
   70 FORMAT(9F12.2,/)
   71 FORMAT(9F12.2,/)
   72 FORMAT(9F12.2,/)
   73 FORMAT(9F12.2,/)
   74 FORMAT(9F12.2,/)
```

```
 75 FORMAT(F15.4,5F12.2,/)
 76 FORMAT(F15.4,5F12.2)
 77 FORMAT(8F12.3,/)
 80 FORMAT(1H1,4X,5HP(MW),7X,8HDC VOLTS,6X,3HRPM,7X,4HFREQ,8X,2HJC,12X
   &,2HVT,10X,2HPF,9X,4HFBAR,10X,2HKW)
 81 FORMAT(8X,2HCS,11X,2HNS,10X,1HZ,9X,3HIPH,7X,5HSLOTS,7X,6HSWIDTH,9X
   &,4HDBAR,7X,4HDCON,10X,3HDPH)
 82 FORMAT(7X,4HDELB,8X,4HDELT,8X,4HDELS,8X,4HDELE,10X,1HS,10X,3HGAP,1
   &1X,1HB,11X,1HA,5X,7HEND ANG)
 83 FORMAT(8X,2HRR,11X,1HD,10X,2HRS,10X,2HLL,9X,2HLC,9X,6HLPRIME,9X,1H
   &E,9X,5HDBSEL,9X,1HT)
 84 FORMAT(8X,2HDA,8X,4HDARM,11X,1HH,10X,2HTW,10X,1HW,9X,5HDELTA,7X,4H
   &FARM,8X,5HACOND)
 85 FORMAT(8X,3HBR1,9X,3HBR2,9X,3HBKG,9X,3HBRM,9X,3HBTM,9X,3HBFF,8X,4H
   &BRPM,7X,4HBTPM,10X,2HBT)
 86 FORMAT(/,2X,13HSPEC.WT.LB/KW,2X,10HTOT.WT.LBS,3X,9HROTOR(LB),2X,10
   &HVOL(CU.FT),2X,10HSPEC. LOAD)
 87 FORMAT(5X,10HEFFICIENCY,3X,10HOHMIC LOSS,3X,9HEDDY LOSS,2X,11HSHIE
   &LD LOSS)
151 FORMAT(//,19H NO ROOM FOR COPPER,/)
    STOP
    END
```

```
      SUBROUTINE MFLD(RHO,PHU,BRHO,BPHI,X0,Y0,DX,DY,AI)
      DOUBLE PRECISION A,B,AI,X0,X1,Y0,DX,DY,PI,P2,AM,BK,BF,XXC,YYC
      DOUBLE PRECISION XX,YY,RHO,Z,PHI,X,Y,F,BRHO,BPHI,BMAG
      DIMENSION A(12,12,8),B(12,12,8)
C              ****************                       ****************
C *** THIS SUBROUTINE CALCULATES THE MAGNETIC FLUX DENSITY IN FREE SPACE
C *** FOR A FOUR POLE ROTOR STRUCTURE USING THE BIOT-SAVART LAW.
C *** A 12X12 ARRAY OF WIRES REPRESENTS EACH COIL SIDE WHICH IS ASSUMED TO BE
C *** RECTANGULAR IN CROSS SECTION.
C *** THE RECTANGULAR CROSS SECTION IS (12*DX)/.0254 INCHES WIDE BY
C *** (12*DY)/.0254 INCHES HIGH.  WHERE WIDE AND HIGH REFER TO THE X AND Y
C *** COORDINATE DIRECTIONS RESPECTIVELY. (SEE FIGURE 30  IN THIS APPENDIX)
C              ****************                       ****************
      PI=3.14159265358993
      PHI=PHU*PI
      P2=PI/2.
      AM=4.E-07*PI
      BK=AM*AI/(2.*PI)
      X1=-X0
      K=1
      X=X0
      Y=Y0
   50 DO 1 J=1,12
      DO 2 I=1,12
      A(I,J,K)=DSQRT(X**2+Y**2)
      Z=Y/X
      B(I,J,K)=DATAN(Z)
    2 X=X+DX
      X=X0
    1 Y=Y+DY
      K=2
      X=X1
      Y=Y0
      DO 3 J=1,12
      DO 4 I=1,12
      A(I,J,K)=DSQRT(X**2+Y**2)
      Z=Y/X
      B(I,J,K)=DATAN(Z)
    4 X=X-DX
      X=X1
    3 Y=Y+DY
      K=3
      DO 5 J=1,12
      DO 5 I=1,12
      A(I,J,K)=A(I,J,1)
    5 B(I,J,K)=B(I,J,1)+P2
      K=4
      DO 6 J=1,12
      DO 6 I=1,12
      A(I,J,K)=A(I,J,2)
    6 B(I,J,K)=B(I,J,2)+P2
      K=5
      DO 7 J=1,12
      DO 7 I=1,12
      A(I,J,K)=A(I,J,3)
    7 B(I,J,K)=B(I,J,3)+P2
      K=6
```

```
      DO 8 J=1,12
      DO 8 I=1,12
      A(I,J,K)=A(I,J,4)
    8 B(I,J,K)=B(I,J,4)+P2
      K=7
      DO 9 J=1,12
      DO 9 I=1,12
      A(I,J,K)=A(I,J,5)
    9 B(I,J,K)=B(I,J,5)+P2
      K=8
      DO 10 J=1,12
      DO 10 I=1,12
      A(I,J,K)=A(I,J,6)
   10 B(I,J,K)=B(I,J,6)+P2
      BRHO=0.00
      BPHI=0.00
      BF=-BK
      K=1
      DO 11 J=1,12
      DO 11 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   11 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      BF=+BK
      K=2
      DO 12 J=1,12
      DO 12 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   12 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      K=3
      DO 13 J=1,12
      DO 13 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   13 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      BF=-BK
      K=4
      DO 14 J=1,12
      DO 14 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   14 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      K=5
      DO 15 J=1,12
      DO 15 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   15 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      BF=+BK
      K=6
      DO 16 J=1,12
      DO 16 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   16 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      K=7
```

```
      DO 17 J=1,12
      DO 17 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   17 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      BF=-BK
      K=8
      DO 18 J=1,12
      DO 18 I=1,12
      F=A(I,J,K)**2+RHO**2-2.*A(I,J,K)*RHO*DCOS(B(I,J,K)-PHI)
      BRHO=BRHO+BF*A(I,J,K)*DSIN(B(I,J,K)-PHI)/F
   18 BPHI=BPHI+BF*(RHO-A(I,J,K)*DCOS(B(I,J,K)-PHI))/F
      RETURN
      END
```

SAMPLE OUTPUT

SUPERCONDUCTING GENERATOR BASE-LINE DESIGN

P(MW)	DC VOLTS	RPM	FREQ	JC	VT	PF	FBAR	KW
20.00	4000.00	6000.00	200.00	29400.00	471.00	.85	.45	1.00
CS	NS	Z	IPH	SLOTS	SWIDTH	DBAR	DCON	DPH
6.00	25.00	2015.00	445.74	336.00	.16	.02	.01	.50
DELB	DELT	DELS	DELI	S	GAP	B	A	END ANG
.50	.50	.75	.50	7.00	.20	1.50	2.94	39.99
RR	D	RS	LL	LC	LPRIME	E	DBSEL	T
9.00	20.39	19.13	4.99	13.79	22.60	5.81	.26	2.90
DA	DARM	H	TW	W	DELTA	FARM	ACOND	
1.686	1.424	.139	.033	14.774	.665	.327	.015	
BR1	BR2	BKG	BRM	BTM	BFF	BRPM	BTPM	BT
-1.73	-1.16	14.45	-I	-1.33	-1.00	-1.45	-1.16	-.28

1	183.30
2	96.19
3	115.67
4	257.32
5	38.02
6	27.15
7	163.09
8	44.39
9	135.41
10	95.19
11	273.62
12	184.68
13	39.27

SPEC.WT.LB/KW	TOT.WT.LBS	ROTOR(LB)	VOL(CU.FT)	SPEC. LOAD	
.0853	1706.42	807.70	35.10	13631.65	15000.00
EFFICIENCY	OHMIC LOSS	EDDY LOSS	SHIELD LOSS		
93.9105	756.14	347.48	193.26		

APPENDIX C

POWER SUPPLY COMPONENT WEIGHT ALGORITHMS

The following weight algorithms were used to calculate component weights for the system point designs described in Table 6.

FUEL

$$W_{FUEL} = 0.3724\ (SPC)\ P_{TURB(M)}\ \Delta t_{on}\ \text{(lbs)}$$

SPC = specific propellant consumption, lbs/(HP-HR)

P_{TURB} = turbine shaft power, megawatts

Δt_{on} = total power generation time, seconds (assumed to be 120 seconds for the point designs)

TURBINE (Reference 2)

$$W_{TURBINE} = 0.3455\ D_T^{2.362}\text{, (lbs)}$$

where

$$D_T = 3.896 \times 10^5/RPM_T \text{ (Turbine tip diameter, inches)}$$

$$RPM_T = \text{Turbine rotational speed}$$

GEAR BOX (Reference 11), Double reduction, three-branch gear box

$$W_{GB} = (88.236/RPM_T)\ (HP)\ (SUM)\text{, (lbs)}$$

where:

HP = mechanical shaft power of the turbine in horsepower

$$SUM = \frac{1}{3}(1 + m_g) + m_g\ (2 + m_g + m_g/M_o) + \frac{1}{3} M_o\ (1 + M_o/m_g)$$

$$M_o = RPM_T/RPM_G = \text{overall gear ratio}$$

$$RPM_G = \text{rotational speed of the generator rotor}$$

m_g is the optimum internal gear ratio and is found from the following expression:

$$2m_g^2 \left[m_g \left(M_o + 1\right) + M_o\right] = \frac{1}{3} M_o \left(M_o^2 + 1\right)$$

A linear approximation to the above expression is given by (R. L. Binsley, Rocketdyne, personal communication):

$$M_g = 0.185\, M_o + .333$$

For each of the point designs in Table 6 involving a gear box, Table 9 lists the pertinent parameters for calculating the gear box weights. The weights were calculated for both the exact and approximate values of m_g; however, the exact values of m_g were used in calculating the gear box weights in Table 6.

TABLE 9

GEAR BOX WEIGHT CALCULATIONS

POINT DESIGN	RPM_T	RPM_G	M_o	m_g (approx)	m_g (exact)	W_{GB}(lbs) (approx)	W_{GB}(lbs) (exact)
2 (PMG)	14,900	18,000	0.82778	0.48614	0.38880	204	182
3 (SCG)	14,900	6,000	2.48333	0.79272	0.76030	487	484
5 (PMG)	10,500	18,000	0.58333	0.44092	0.340675	602	507
7 (SCG)	10,500	6,000	1.7500	0.65675	0.592207	1183	1156

<u>HIGH POWER TRANSFORMER (T1)</u>, (References 4, 13)

$$W_{T1} = 0.0505 \left(\frac{\Delta t_{on}}{120}\right)^{\left\{0.337 \left(\frac{V_o}{100}\right)^{-0.0413}\right\}} \times \left[0.693 + 0.307 \left(\frac{P_{1(M)}}{25}\right)^{-0.79}\right]$$

$$\times \left[0.931 + 0.069 \left(\frac{V_o}{100}\right)^{1.3}\right] \times \left[0.242 + 0.758\, f^{-0.926}\right] \times P_{1(KW)} \quad \text{(lbs)}$$

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PERMANENT MAGNET AND SUPERCONDUCTING GENERATORS IN AIRBORNE, HI--ETC(U)
AUG 79 H L SOUTHALL , F C BROCKHURST
UNCLASSIFIED AFAPL-TR-79-2073

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V_o = DC output voltage required at the load (KV)

f = alternator frequency (KHz)

$P_{1(M)}$ = transformer output power (MW)

$P_{1(KW)}$ = transformer output power (KW)

LOW POWER TRANSFORMER (T2), (References 4, 13)

$$W_{T2} = 0.1275 \left(\frac{\Delta t_{on}}{120}\right)^{0.281} \times \left[0.612 + 0.388 \left(\frac{P_{2(M)}}{2.5}\right)^{-0.985}\right]$$

$$\times \left[0.608 + 0.392 \left(\frac{V_o}{200}\right)^{0.71}\right] \times f^{-0.767} \times P_{2(KW)} \quad \text{(lbs)}$$

$P_{2(M)}$ = output power of low power transformer (MW)

$P_{2(KW)}$ = output power of low power transformer (KW)

THREE PHASE RECTIFIER (References 4, 13)

$$W_{RECT} = 0.0073 \left[0.945 + 0.055 \left(\frac{V_o}{100}\right)^{2.2}\right] \times \left(\frac{\Delta t_{on}}{60}\right)^{0.83} \times P_{(KW)} \quad \text{(lbs)}$$

$P_{(KW)}$ is the input power to the rectifier in kilowatts and is $P_{1(kw)}$ for the high power branch of the circuit or $P_{2(kw)}$ for the low power branch.

NOTE: V_o must be chosen correctly to reflect the correct weights for the high and low power branches since V_o is different in the two cases.

LC FILTER (References 4, 13)

$$W_{LC} = \frac{1.81 \times 10^{-3}}{f} \times P_{(KW)}, \text{ (lbs)}$$

where $P_{(KW)}$ is defined under <u>THREE PHASE RECTIFIER</u>. The following assumptions were made concerning the LC filter:

1% peak-to-peak ripple allowed in the load voltage;
inductor energy storage density = 25 joules/lb;
capacitor energy storage density = 100 joules/lb;
conduction overlap angle = 30 degrees;
diode rectification (i.e., no firing angle control).

<u>PMG COOLING SUBSYSTEM</u> (Reference 2)

$$W_c = 130\, P_{G(M)}^{0.375} + \frac{(100 - \eta_G)}{\eta_G} \times \Delta t_{on} \quad \text{(lbs)}$$

$P_{G(M)}$ = generator output power in megawatts times the number of generator units required to supply the required load power

η_G = generator efficiency in percent

<u>SUPERCONDUCTING GENERATOR COOLING SUBSYSTEMS</u>

Stator Cooling (Pressurized Water)

$$W_c = P_{G(M)} \times \frac{(100 - \eta_G)}{\eta_G} \times \dot{W}_c \times \Delta t_{on} \quad \text{(lbs)}$$

$$\dot{W}_c = 1.0 \text{ lb/(MW-SEC)}$$

Cryogenic Cooling (Liquid Helium)

$$W_{cryo} = (1.09)\ (1.10)\ (\dot{L})\ (MT) \quad \text{(lbs)}$$

1.09 = 0.80 + 0.29 accounts for the weight of the dewar system and the stored liquid helium, respectively.

1.10 = factor to account for losses

$\dot{L}$ = rotor helium flow rate required in liters per hour. For the 10 MW machines, $\dot{L}$ is assumed to be 20 liters/hr and for the 20 MW machines, $\dot{L}$ is assumed to be 25 liters/hr.

MT = mission time (duration) in hours, assumed to be 10 hours.

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☆U.S.Government Printing Office: 1979 — 657-084/279